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Laboratory of Land Use, Mobility and Environment
DICEA - Department of Civil, Building and Environmental Engineering
University of Naples Federico II
Piazzale Tecchio, 80
80125 Naples (Italy)

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Land transformation and new road infrastructures. An analysis on direct and inducted impacts due to the Brebemi highway

Rossella Moscarelli [a]*, Marialaura Giuliani [b]

[a] Department of Architecture and Urban Studies
Politecnico di Milano, Milano, Italy
e-mail: rossella.moscarelli@polimi.it
ORCID: https://orcid.org/0000-0001-6967-1513
*Corresponding author

[b] Department of Civil Engineering, Architecture, Land, Environment and of Mathematics– DICATAM
University of Brescia, Brescia, Italy
e-mail: marialaura.giuliani@unibs.it
ORCID: https://orcid.org/0009-0007-5602-4561

Abstract

The paper reflects on the relation between land transformations and the construction of new road infrastructure, by focusing on the quantification of soil consumption related to highways. Such infrastructures are relevant cases since they can impact both directly and indirectly on the land cover: directly if we consider the soil sealing produced by the infrastructure itself (the natural soil urbanized to realizing the highway); indirectly if we consider the inducted transformations enhanced by the realization of the highway (e.g. other new infrastructures connected to the highway or productive and logistic areas close to it).

The paper focuses on the Italian case study of the Brebemi highway, recently realized in the Lombardy Region (Italy). It represents one of the first scientific quantification of direct and inducted land transformations related to this new mobility infrastructure. The results demonstrate the heavy direct impact on soil consumption (278.3 ha), but also an alarming inducted soil consumption due to the secondary infrastructures realized in connection to the new highway (116.8 ha) and to the urbanization increase in a buffer zone of 1km (650 ha).

Keywords

Soil&land consumption; Soil sealing; Infrastructure; Highway; Brebemi

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1. Road infrastructures and environmental impacts: the case of the highways

The paper investigates the impacts on land transformations and on the increase of soil sealing derived from the construction of a new road infrastructure, such as highways. The analysis focuses on land transformations producing soil consumption, namely on the transformation of natural soil (rural or wooded) into urbanized and sealed areas. In this sense, soil consumption can be regarded as land take (Nuissl et al., 2009), i.e. as previously undeveloped soil taken into the built housing, utilities, transport, industry, commercial and recreation activities (Huber et al., 2008).

Many researches were carried out to analyze and quantify the recent urban transformations in the Italian context, by focusing on their effects on the soil sealing and land-use changes (Munafò, 2024; Ronchi et al., 2023; Zullo et al., 2015; Mazzeo & Russo, 2016; Boschetto & Bove, 2012). The study discussed in the paper contributes to enriching such debate by considering the specific case of land transformations due to a new highway (Iacono et al., 2015). Thus, it can be regarded as part of a broader reflection on the environmental impacts of road infrastructures, generated both in the phases of realization and operation.

For what concerns the realization phase, the most relevant environmental impacts are those on land transformations (Barberis, 2005; Castiglioni et al., 2015), ecosystems fragmentation and modification (Fabietti et al., 2011; González-Gallina et al., 2013; Koemle et al., 2018; Madadi et al., 2017), alteration of the hydrological network (Fabietti et al., 2011) and of animals' habitats and behaviors (Benítez-López et al., 2010; Halfwerk et al., 2011; Long et al., 2017; Paemelaere et al., 2023; Summers et al., 2011).

Moreover, the operation of the infrastructure, with its relevant vehicular traffic, causes other environmental negative impacts: pollution on air and water, included groundwater through runoff and percolation (Kibblewhite, 2018; Nikolaeva et al., 2017; Uliasz-Misiak et al., 2022; Werkenthin et al., 2014); impacts on vegetation due to the deposition of road dust and nitrogenous compounds (Feng et al., 2021; Gadson et al., 2009; Rahul et al., 2014); detrimental consequences on local fauna, together with its direct mortality (Fabietti et al., 2011; Orlowski, 2008; Qin et al., 2023; Van Der Ree et al., 2015); negative effects on human beings, due to the traffic noise, to the direct inhalation of contaminants and to the assumption of contaminated food produced in the rural areas closed to the highway (Gargiulo & Romano, 2011; Kibblewhite, 2018; Kole et al., 2017; Turer et al., 2003).

Many of these impacts can affect not only the territory directly involved in the realization of the road, but also a broader buffer zone. The most intuitive case is probably the air pollution caused by exhaust and non-exhaust emissions, whose contaminants can reach, with adverse meteorological conditions, a distance of many kilometers from the roadside. Richard Forman, initiator of the road ecology, was one of the first who theorized the so-called *road-effect zone* (i.e. the buffer area in which it is possible to detect environmental impacts caused by the infrastructure) and who tried to quantify it by studying the case of some American highways (Forman, 2000). In his research, he analyzed a highway of four lanes close to the city of Boston by considering its impacts on different ecological aspects (local fauna and flora and hydrological system). The result was the definition of a road-effect zone of 600 meters from both sides of the highway. More recently, other studies have identified other dimensions for the road-effect zone: 400 meters (Wu et al., 2014), 250 –1,000 meters (Eigenbrod et al., 2009) and 1,000-1,300 meters (Theobald et al., 2011). All these studies agree on the huge environmental impact of a large infrastructure (Coffin, 2007), even if it emerges a high variability depending on the typology of the road, on the impacts investigated and on the specific landscape crossed (Feng et al., 2021). It is still little investigated how quantifying the road-effect zone in the case of the impacts on land transformations and soil consumption, object of the analysis. Nevertheless, the influence of the infrastructure in the increase of urban sprawl is well known (Pileri, 2024; Castiglioni et al., 2015; Romano et al., 2017; Squires, 2002). As a matter of fact, many scholars have described how a highway can be regarded as a lever of the land transformations in the surrounding territory (Vendemmia, 2011), by enhancing the construction of new connecting roads and urbanized areas, both productive and residential (Assennato et al., 2019; Munafò, 2022; Pileri, 2022); still, attempts and procedures to quantify this effect are lacking. In order to expressly measure this influence, the study conducted and here reported on the Italian highway Brebemi (Brescia-Bergamo-Milan) investigates the impact on soil consumption caused not only by the infrastructure itself (hereby defined as direct soil consumption, Dsc), but also caused by the new infrastructures connected to the highway (linear inducted soil consumption, linear Isc) and by new urbanized areas located in a buffer zone of 500m from each side of the highway (areal inducted soil consumption, areal Isc).

In the following, the case study is introduced, its relevance and the reasons for which the Brebemi highway was selected as a valid sample. Then, the methodology of the quantification of the direct and inducted soil consumption is described, together with the dataset used to calculate the land cover transformations. After that, the results of the analysis are discussed, for both the direct and inducted soil consumption cases. Such results are then discussed by considering their weight on the general variation of urbanized areas and soil consumption in the municipalities crossed by the highway. This analysis allows to better understand how much these two aspects have changed in the pre-Brebemi period, e.g. before the realization of the highway, and post-Brebemi period, e.g. after its construction. In the conclusions, the limits of the analysis and the hypotheses of future development of the research are commented.

2. The case study: the Brebemi highway in Lombardy Region

The Brebemi highway is located in the Lombardy Region, in the north of Italy, and it connects the cities of Brescia and Milan by a track of 62 kilometers (Fig.1). It crosses 27 municipalities, in four different provinces (Brescia, Bergamo, Lodi and the Metropolitan area of Milan).

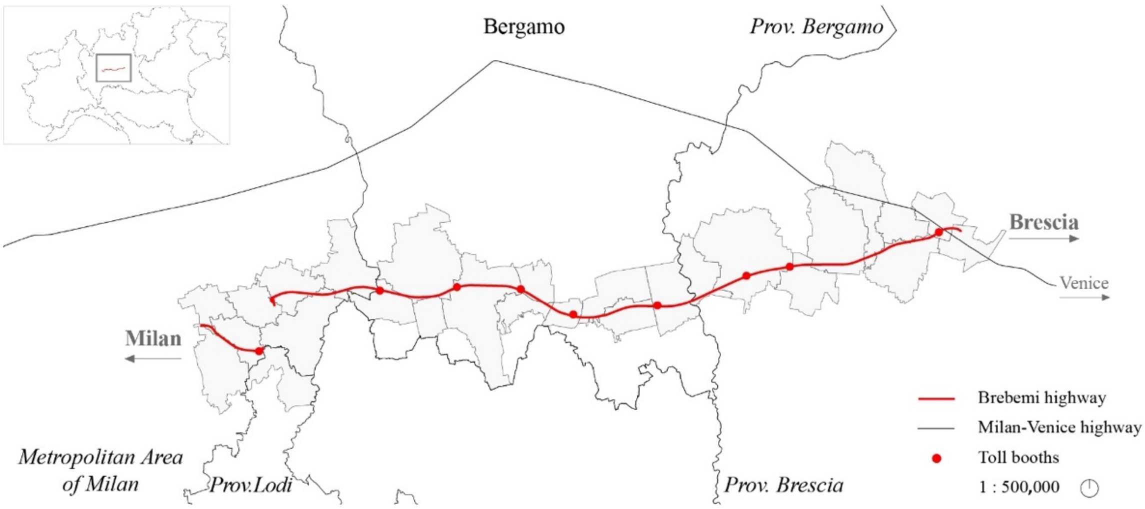

Fig.1 The Brebemi highway.

The Brebemi highway was selected as case study for the following reasons:

- its realization is recent (the construction started in 2009 and ended in 2014, while the project had begun to be discussed before the 2000s) and, therefore, it is possible to deeply study the land transformations derived from it. As a matter of fact, the best dataset on land cover in the Lombardy Region (the DUSAF[1]) provides data for the years 1999, 2007, 2012, 2015 and 2018[2]. The availability of such data allows us to define two periods of analysis, one to study the situation pre-Brebemi (by taking the period 1999-2007) and the other to study the situation post-Brebemi (by taking the period 2007-2018);

[1] DUSAF is a land use analysis and monitoring tool of the Lombardy Region. It is a vector resource capable of classifying the territory on the basis of land use into five levels and five related sub-levels, with a spatial resolution of 1:10000.

[2] Actually, a latest version of the DUSAF was recently released (DUSAF 7, referred to 2021), which however was not considered in this analysis because it was subsequent to the collection of the results.

- its importance in the public debate (local, regional and national). The highway was originally proposed with the stated purpose of relieving traffic congestion in the area of Brescia but, in the past such as at the present, it has been strongly criticized since there was already a highway connecting Brescia and Milan (the Milan-Venice highway) that it is still the most used due to the less expensive toll (Cuda et al., 2015; Giuliani, 2023). Despite such interest in public debate, the case was still poorly studied by scholars and there is not any precise quantification of soil consumption due to the highway[3]. There is just a preliminary evaluation done before the conclusion of the work (Di Simine & Salata, 2014), to which the results of the present analysis will be compared in the following sections;
- its location in a plain and rural context with a high natural value. The Brebemi crosses four regional parks related to the rivers Oglio, Serio and Adda and the regional Milan Southern Agricultural Park in last section of the track from Liscate to Milan. In addition, a huge portion of the territory crossed by the Brebemi highway is classified by the Lombardy Region as *Priority areas for the biodiversity*[4] (Fig.2);

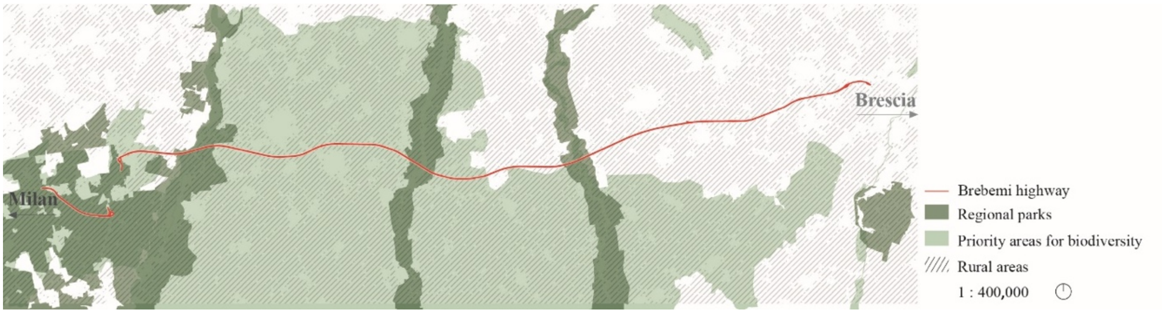

Fig.2 The Brebemi highway and the natural and rural environment.

- its relevance in the field of the soil consumption studies: on the one hand, because in the Italian context the road infrastructures represent the 30-40% of the national soil consumption (Assennato et al., 2019); on the other, because the Lombardy is one of the first Italian region for soil consumption and soil sealed (Munafò, 2024). In this sense, the case of the Brebemi is emblematic since the highway is located in a dense urbanized area where many land transformations have occurred in the last years.

3. Methodological issues to quantify direct and inducted soil consumption

All the calculations on land cover and its transformation due to the Brebemi highway were carried out with Gis analysis (in particular, using the ArcGIS software) and thanks to the regional database DUSAF. Such database is organized with the same legend and classification of the European Corinne Land Cover: class 1 refers to artificial surfaces, class 2 to agricultural areas and class 3 to forest and seminatural areas. More specifically, class 1.4 represents non-agricultural vegetated areas.

On the basis of this classification, the analysis considers:

- as urbanized areas all those areas whose land cover belongs to class 1, except the class 1.4 (namely urbanized areas are made on the sum of the classes 1.1,1.2 and 1.3);
- as soil consumption, the transformation of natural areas (namely all those areas whose land cover belongs to the classes 1.4, 2 and 3) into urbanized areas.

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[3] Following the prescription of the *Comitato Interministeriale per la Programmazione Economica* (CIPE), the society who has realized the Brebemi had to conduct a monitoring on the main environmental impacts due to the construction and operation of the highway. The monitoring ended in 2018 and includes also the soil consumption. At the present the data are not freely available, but just on request and with precise limitation about their diffusion.

[4] The identification of Priority Areas for the Biodiversity in the Lombardy was inspired by the ecoregional conservation approach developed in the 1990s by WWF and The Nature Conservancy (TNC). Assuming this approach, an ecoregion is regarded as a terrestrial (or aquatic) unit relatively large that contains a distinct combination of natural communities that share most species, dynamics, and environmental conditions (Bogliani et al., 2007).

A relevant note is that soil consumption does not correspond to the net variation of the urbanized areas in a certain period. Indeed, the net variation would count both the increase of new urbanized areas (determining a positive variation) and of new natural areas (determining a negative variation). Such phenomena of re-naturalization, namely of transformation from urbanized to natural areas, are quite common in cases of infrastructures, since during the construction period the urbanized areas detected by the land cover database are wider than the final ones (for instance, they also include the building site areas). The analysis has considered the land cover features in three different years: 1999, 2007 and 2018, while the soil transformations were observed in the periods 1999-2007 (pre-Brebemi) and 2007-2018 (post-Brebemi).
The identification of the areas of study was the first step of the analysis. They are:

1. the area of the Brebemi highway (meant as "footprint" to the ground) related to the study of the direct soil consumption (Dsc);
2. the area of the infrastructures (meant as "footprint" to the ground) connected or related to the Brebemi highway, related to the study of the linear inducted soil consumption (linear Isc);
3. the area close to the Brebemi highway, namely a buffer zone of 500m from each side of the road, related to the areal inducted soil consumption (areal Isc[5]).

The area of the Brebemi was obtained starting from the linear track of OpenStreetMap. From the regional official database[6] it was possible to extract the information about the width of the highway, namely the lanes and all the other complementary elements included in the highway, as the emergency lane, the service areas or the toll booths. The area of the infrastructures refers to the new roads, built in the post-Brebemi period (2007-2018) to serve the highway or to be in connection with it. In the following, three categories are presented; they aggregate these infrastructures on the basis of the motivation for which they have been regarded as inducted by the realization of the Brebemi highway (Fig.3):

a) new roads realized to link the Brebemi highway with the territory;
b) modification of already existed roads, interrupted or deviated by the Brebemi;
c) new roads, not physically connected to the highway, but realized as Brebemi compensatory interventions.

(a) (b) (c)

Fig.3 Example of infrastructure's types: (a) West Beltway in Caravaggio (category 1); (b) interventions and deviations in Caravaggio (category 2); (c) Cassano Beltway (category 3)

[5] Note that the portions of this area outside the borders of the municipalities crossed by the highway were not consider in this classification. In any case, these portions have a little and negligible contribution on the entirety of the 1km buffer zone (500m from each side of the road).
[6] "Database Topografico (Dbt) Regionale" available on the Territorial Information System (SIT) of Lombardy Region.

Once identified the infrastructures inducted by the Brebemi, it was necessary to consider their different physical features. The linear extensions were taken from the official regional data[7], while the width was calculated by distinguishing 4 different categories based on the typology of the roads (Tab.1).

Typology of road		Dimension of road		
Name	**Description**	**Number of lanes**	**Total width [m]**	**Length [km]**
Type_1	Extra-urban main roads with two lanes in each direction	4	22	19.1
Type_2	Extra-urban secondary roads with two lanes	2	10.5	60.8
Type_3	Local roads in urban areas	2	9.5	24.1
Type_4	Road junctions	1	6	27.9

Tab.1 Classification of inducted infrastructures (linear inducted soil consumption) on the basis of their geometrical features (taken from the official roads classification introduced by the Ministry of Infrastructure and Transportation, November 2001

The two classifications introduced are overlapped in Tabl.2.

Type of roads inducted by the Brebemi	Typology of road	Length [km]
New roads connecting the Brebemi and territory	Type_1, Type_2, Type_3, Type_4	116.3
Modification of roads interrupted or deviated by the Brebemi	Type_2, Type_3	8.8
New roads of compensation interventions	Type_2, Type_3	6.8

Tab.2 Cross-classification of typologies of roads inducted by the Brebemi and of their geometrical features

Finally, the study buffer area of the Brebemi, related to the areal Isc, was identified starting from the track of the highway. The dimension of the buffer (500m from each side of the road) depends on theoretical evidence that has demonstrated how the soil consumption inducted by the presence of a new infrastructure (as in the case of logistics or productive hubs) is concentrated in a distance between 0 and 500m from it (Munafò, 2022). Since the buffer area includes also the Brebemi itself and some part of the infrastructures connected to the highway, to avoid counting twice these values the contributions derived by the Brebemi and by these other infrastructures were not included in the calculation of the indicators related to the buffer area.

After having identified the areas of study, the urbanized areas and the soil consumption were obtained by intersection with them and the land cover in the three years considered (using the "intersect" command on the GIS software). The need to identify the footprint of infrastructures (both BreBeMi and induced linear infrastructures) and then intersect them with the DUSAF data arises from the fact that the latter is not provided at a spatial scale that allows for an accurate representation of the actual dimensions of the infrastructures. Again, the same "intersect" command was used to pass from the urbanized areas in the three years considered to the soil consumption in the two periods, thus identifying areas that experienced land cover transformation and isolating those that changed from natural to urbanized areas.

From these results, two classes of indicators were constructed: synchronic, related to each of the years considered and to the relevant urbanized areas; diachronic, capturing the urbanized areas evolution during the two periods (1999-2007 and 2007-2018), namely the soil consumption registered. To be more precise and to sum up the previous considerations, the indicators considered are reported in Tab.3.

[7] "Infrastrutture della mobilità" available on the Territorial Information System (SIT) of Lombardy Region.

Synchronic indicators	Diachronic indicators
Urbanized areas – UA [ha]: soil belonging to the DUSAF 1.1, 1.2, 1.3 classes.	Soil consumption – SC [ha]: soil belonging to DUSAF 1.4, 2, 3 classes that are transformed into 1.1, 1.2, 1.3 classes within the considered time horizon.
Urbanized coefficient – UC [%]: ratio between the urbanized areas and the total municipal surface in a certain year.	-
Direct urbanized areas – Dua [ha]: urbanized area of the Brebemi highway route.	Direct soil consumption – Dsc [ha]: soil consumption due to the construction of the Brebemi highway.
Linear induced urbanized areas – linear Iua [ha]: urbanized areas belonging to the road infrastructure supporting Brebemi.	Induced linear soil consumption – linear Isc [ha]: soil consumption due to the construction of road infrastructure supporting Brebemi.
Areal induced urbanized areas – areal Iua [ha]: urbanized areas within the 1km buffer zone, excluding the direct and linear induced urbanized areas included in the buffer zone.	Induced areal soil consumption – areal Isc [ha] – soil consumption within the 1km buffer zone and the considered time horizon, excluding the direct and linear soil consumption included in the buffer zone.
Incidence coefficient of urbanized areas – (D, L, A)uI or TuI_B [%]: ratio between the direct, linear induced and/or areal induced urbanized areas and the total urbanized areas in the municipality.	Incidence coefficient of soil consumption– (D, L, A)cI or TcI_B [%]: ratio between direct, linear induced and/or areal induced soil consumption and total soil consumption in the municipality.
-	Speed of variation of urbanized areas – (D, L, A)Svar or $TSvar_B$ [ha/year]: direct, linear induced and/or areal induced soil consumption per year on average within the considered time horizon.

Tab.3 Synchronic and diachronic indicators valuated for the analysis of Brebemi direct and induced effect on land cover trasformations

4. Results: the direct and inducted soil consumption of the Brebemi highway

The analysis has brought to the quantification of soil consumption due to the realization of the Brebemi highway. Totally, it was calculated a soil consumption, namely a transformation from natural to urbanized areas in the post-Brebemi period, of 1045.1 ha, formed by: Dsc, produced by the Brebemi highway, of 278.3 ha[8]; linear Isc of 116.8 ha; areal Isc of 650 ha (Fig.4-5). It is relevant to note that to realize the new infrastructures (the Brebemi highway and the inducted roads) it was "reused" just a minimum part of already urbanized areas: just 10.5 ha in the case of the Brebemi (the 3% of the total urbanized area of the highway) and 28.7 ha in the case of the other roads (the 20% of their areal track).

The results show that the weight of the Isc corresponds to more than 275% of the soil consumption due to the highway itself. In particular, the areal Isc is the most relevant part since it weighs more than 84% on the total.

On average over the municipalities crossed, the areal Isc corresponds to 24 ha, while the linear Isc corresponds to 2.6 ha. Deepening the analysis, it is possible to note how in some municipalities the areal Isc reaches quite significant values: it is the case of Chiari, with more than 92 ha, or of Caravaggio, Antegnate, Calvenzano and Treviglio which reach respectively the values of 79 ha, 40.9 ha, 36.5 ha and 36.2 ha. The same can be seen in the linear case, for example in the municipalities of Roncadelle and Vignate, with respectively more than 9 and 12 ha, and Calcio, Casirate d'Adda and Caravaggio, with more than 7 ha. Such variability in the results

[8] This data appears quite distant from the other discussed previously in the literature where the estimated soil consumption of the Brebemi highway, even if quantified before its completion, was 309.5 ha, while the urbanized area was assumed to be 356.4 ha (Di Simine, Salata, 2014).

reflects the different distribution of new urbanized areas or of new infrastructures related to the Brebemi: this depends on the logistic and productive hubs in some municipalities, which may determine a higher value of areal Isc, or on new beltways as in Caravaggio (*West Beltway*), Calcio (*South Beltway*) and Casirate d'Adda (*Connection between West Treviglio-Casirate d'Adda tollbooths*), which cause alone a high value of linear Isc, namely of respectively 5.4 ha, 7.8 ha and 6.6 ha.

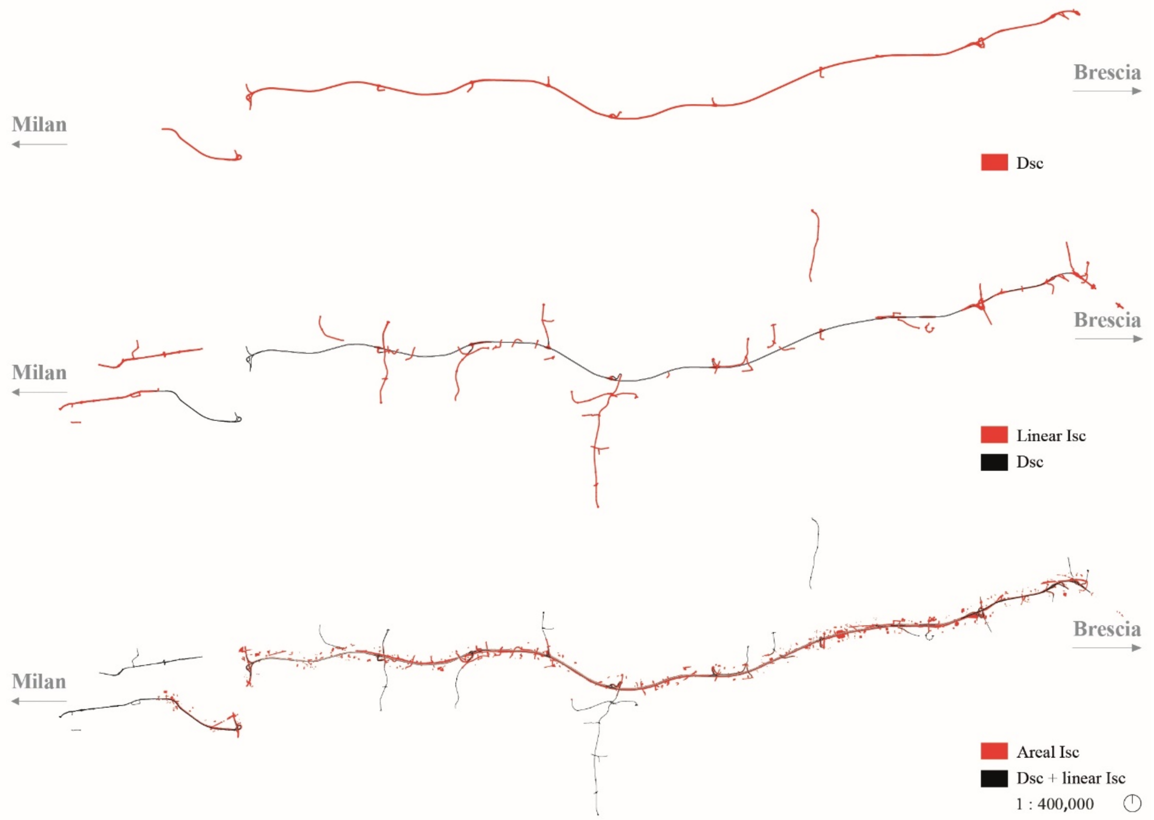

Fig.4 Soil consumption produced by the Brebemi highway divided in direct and inducted (linear and areal)

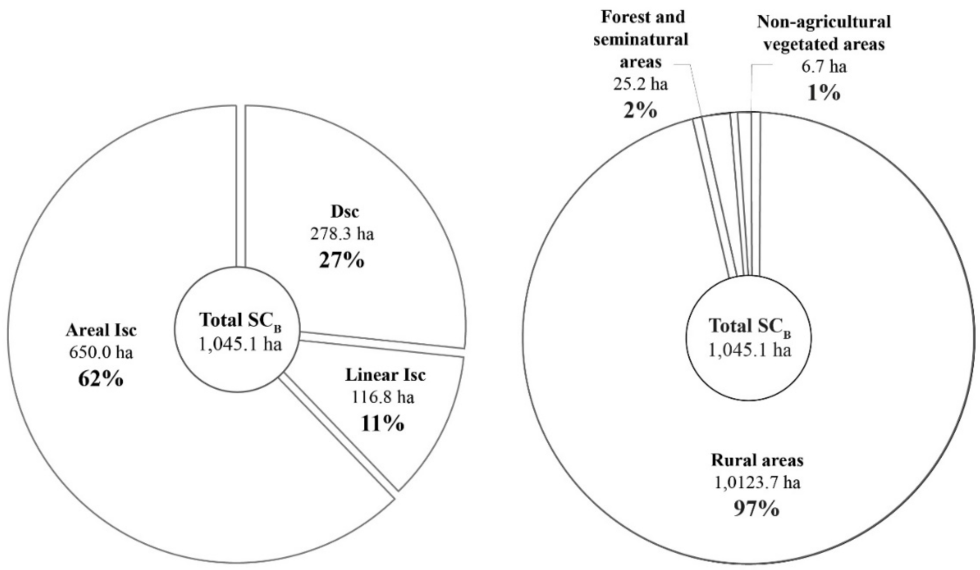

Fig.5 Main results about the soil consumption produced by the Brebemi highway. SC$_B$ stands for Soil Consumption of Brebemi highway

A second finding emerges by analyzing the natural areas lost due to the Brebemi and its inducted transformations. In total, soil consumption has been made mainly on rural areas (1013.7 ha, almost the 97% of the total), while the rest has determined a loss of forest and seminatural areas (25.2 ha, more than 2%)

and non-agricultural vegetated areas (6.2 ha, less than 1%). Moreover, 54% of the total soil consumption affects high valued landscapes: 157.6 ha of soil consumption regard regional parks (49 ha caused by Dsc, 21.7 ha by linear and 86.9 ha by areal Isc) while 537.5 ha[9] involve regional priority areas for the biodiversity (152.1 ha caused by Dsc, 60 ha by linear and 325.4 ha by areal Isc).
In sum, the results show the relevant impacts of the Brebemi highway on the transformation of the land cover, not only for the realization of the infrastructure itself (Dsc), but also for all those inducted changes produced both by new infrastructures connected to the Brebemi (linear Isc) and by the urban sprawl along it (areal Isc) (Fig.5).

5. A reflection on the results: the weight of Brebemi highway in the soil transformations

The results just presented need to be discussed by contextualizing them in a broader frame, to better understand how much the soil consumption derived from the Brebemi, both direct and inducted, has been relevant.
A useful comparison can be done by considering the national data on soil consumption elaborated yearly by ISPRA (the Italian Institute for Environmental Protection and Research). Taking the last report, the Lombardy was the third Italian region for soil consumption in the period 2022-2023, with a value of 780 ha, while Brescia province has consumed 147 ha (Munafò, 2024). This data can provide us a referring point: the soil consumption of the Brebemi, 1,045.1 ha, corresponds to more than the 130% of the soil consumption of the whole Lombardy Region in the last year, and almost ten times the soil consumption occurred in the Brescia Province. These results appear particularly impressive if we consider the different spatial scales of the terms in the comparison[10] and if we notice that 1,045.1 ha correspond to a soil consumption generated by a single infrastructure that it is not the only realized in the Lombardy Region in the last years.
On a local scale, another interesting comparison can be done by calculating how much the Brebemi, with its direct and inducted effects, has affected the total amount of urbanized areas and soil consumption in the municipalities crossed by the highway.
As a first analysis, the increase of the urbanized area determined by the Brebemi can be measured especially by considering the areal induced urbanized areas (areal Iua) and by making a comparison between the land cover pre-Brebemi (period 1999-2007) and post-Brebemi (period 2007-2018). Considering the 1km (500m from each side of the road) buffer zone of the Brebemi highway, the total amount of areal Iua in the three different years of the analysis (1999, 2007, 2018) has changed from 671 ha in 1999, to 882 ha in 2007 (+211 ha in the period 1999-2007), reaching 1.435 ha in 2018 (+553 ha in the period 2007-2018). More specifically, as shown in Figure 6, the areal Iua in the 1km buffer zone of the Brebemi have increased in all the municipalities crossed (except for just two cases). The ratio between the areal Iua in the 1km buffer zone and the urbanized areas in the whole municipality (namely the Incidence coefficient of the areal induced urbanized areas, AuI) gives the weight of the former on the local context (Fig.7). In 1999, before the realization of the Brebemi highway, 15 municipalities on 27 presented a ratio under 10%, 10 of them between 10 and 25% and just 2 of them over 25%. In 2018, after the realization of the Brebemi highway, the situation is quite different: just 6 municipalities have maintained a ratio under 10%, while 11 municipalities display a ratio between 10 and 25% and 10 exceed the 25%. Some cases are significant since they have moved from values under 10% to values over 25%, as occurred in the municipalities of Calcio and Urago d'Oglio.
These data suggest a clear contribution of the Brebemi highway on the land transformations occurred in the municipalities considered and also describe an alarming modification of the territory.

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[9] Note that this amount overlaps with soil consumption in regional parks for 130.7 ha.
[10] To give an idea, the area limited by the administrative boundaries of the municipalities crossed by the Brebemi (40,680 ha) represents only the 8.5% of the Brescia Province surface and the 1.7% of the Lombardy Region surface.

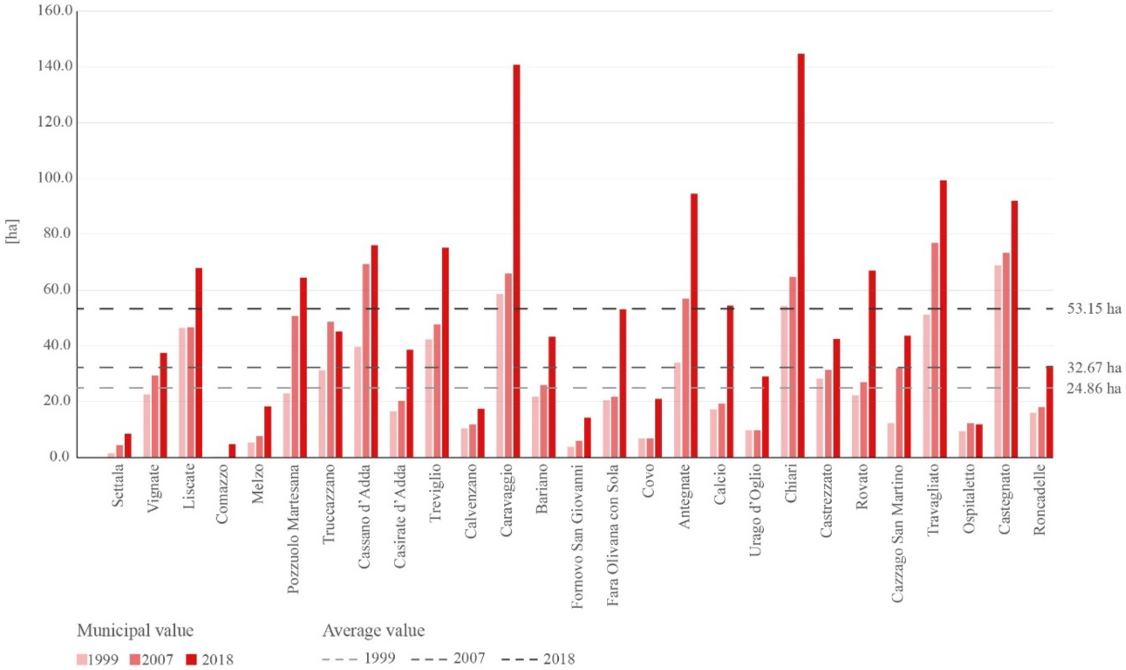

Fig.6 Areal induced urbanized areas in the 1km buffer zone of the Brebemi in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

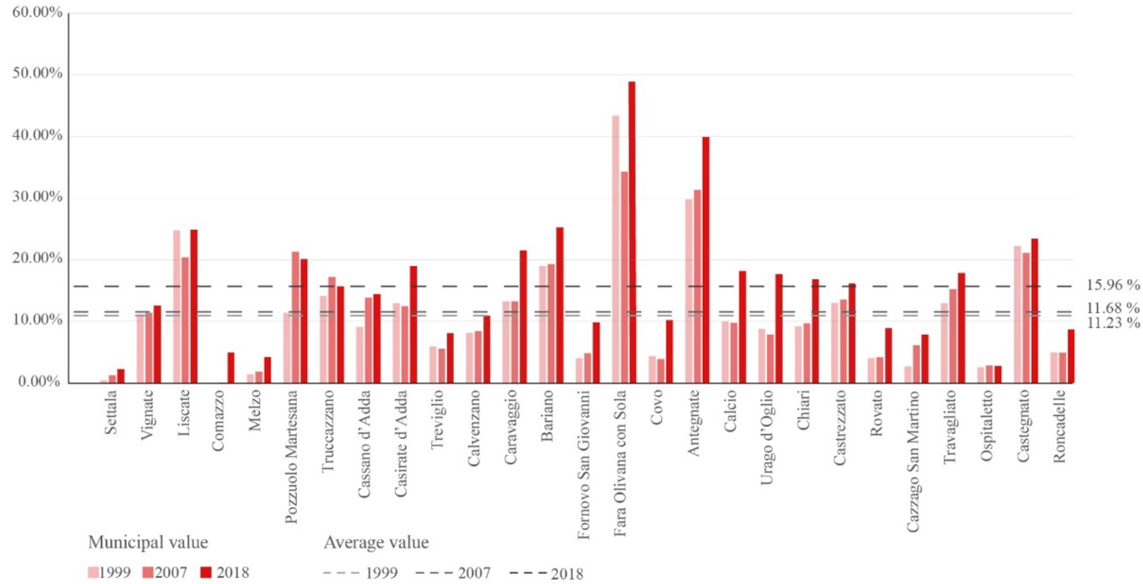

Fig.7 Incidence coefficient of areal induced urbanized areas in each municipality in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

The speed of variation, namely the ratio between the value of the soil consumption in a period and the period itself, is another useful indicator that can validate how the situation has changed in the two scenarios, pre-Brebemi and post-Brebemi. Considering the Speed of variation of areal induced urbanized areas (ASvar), with reference to its average value, the indicator almost duplicates, increasing from 0.98 ha/year in 1999-2007 to 1.86 ha/year in 2007-2018. Regarding the single values, the indicator increased in the period post-Brebemi in almost all the municipalities crossed and in some cases with relevant values (Fig.8): e.g. in the municipality of Caravaggio, where the speed of variation has passed from a value of +0.91 ha/year in the period 1999-2007 to +6.8 ha/year in the period 2007-2018. Similarly, in the municipality of Chiari the indicator pre-Brebemi was +1.3 ha/year, while that one post-Brebemi arrives to 7.2 ha/year.

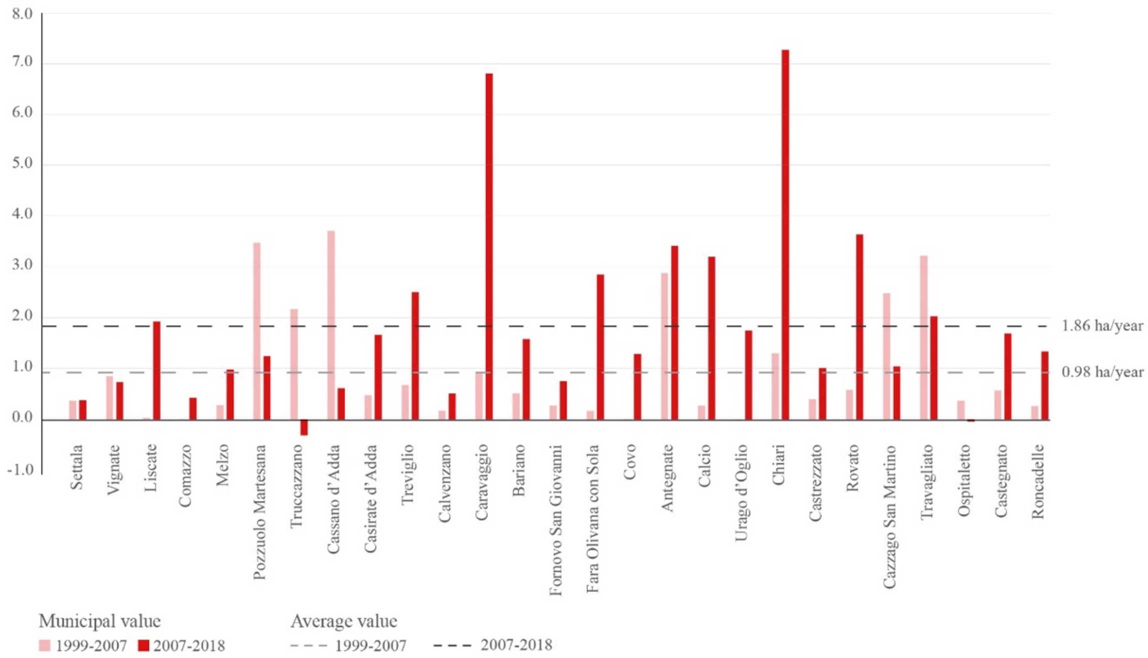

Fig.8 Speed of variation of areal induced urbanized areas in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

In the same way, the urbanization coefficient (i.e. the ratio between the urbanized surface and the total municipal surface in a certain year) has changed in each municipality in the pre and post-Brebemi period: in particular, 7 municipalities experienced an increase at least of the 30% of their urbanization coefficient from 2007 to 2018 (just two in the period 1999-2007), among which we find Calcio with an increase of the 52%, and Fara Olivana con Sola, with a +72% (Fig.9).

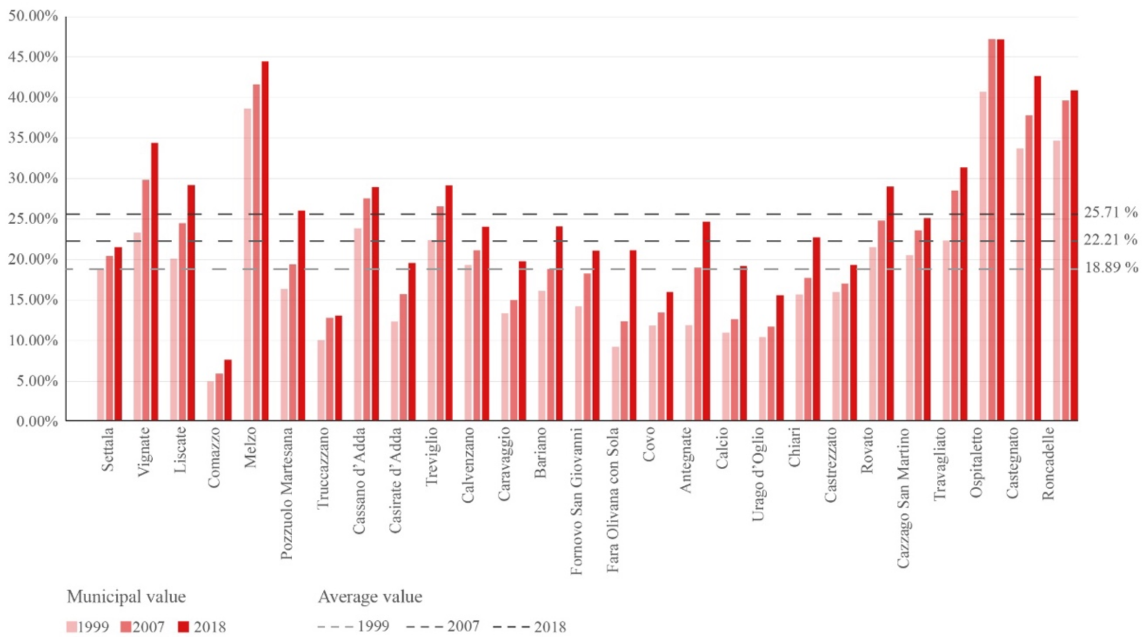

Fig.9 Urbanized coefficient of the municipalities crossed by the Brebemi in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

In addition to the speed of variation, it is useful to consider now another diachronic indicator, thus moving from the values of urbanized areas in the different years to the land cover transformations in the periods 1999-2007 and 2007-2018: in this way it is possible to calculate how much the soil consumption of the Brebemi, both direct and inducted, has affected the total amount of soil consumption in the municipalities crossed by the highway. As shown in Figure 10, the analysis has considered separately each component of soil consumption related to the Brebemi, the Dsc and the linear and areal Isc. For each of them it was calculated the respective incidence on the total amount of the municipal soil consumption, by elaborating different Incidence coefficients of soil consumption, as a Direct-consumption Index (DcI), a Linear-consumption Index (LcI) and an Areal-consumption Index (AcI).

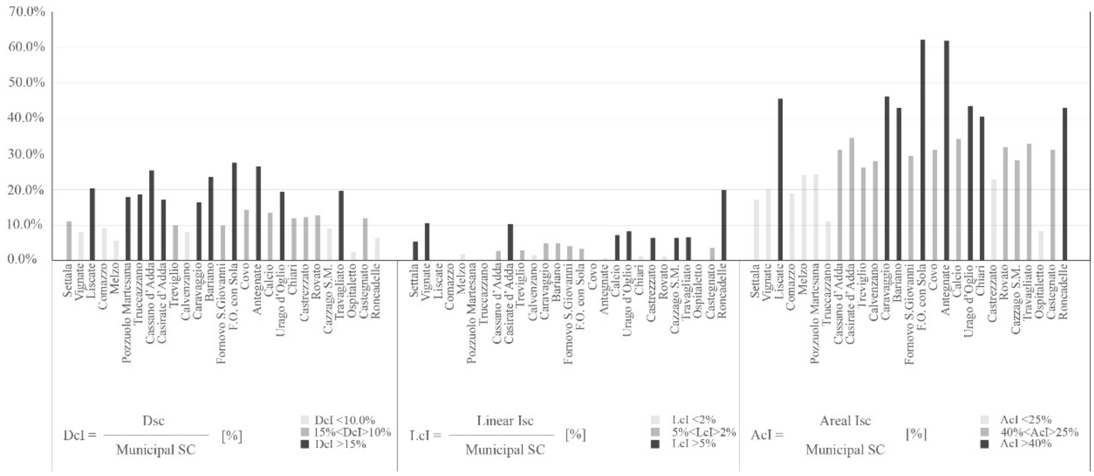

Fig.10 Incidence coefficient of soil consumption (direct and inducted) in the period 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

Starting from the DcI, in 11 municipalities (more than the 40% of the total amount) the value is quite relevant since it exceeds the 15%; in 9 municipalities (the 33%), the value appears between the 15% and the 10%; in the rest of the cases the incidence of the Brebemi on the total amount of the soil consumption registered in the period 2007-2018 is still greater than the 5% (except for Ospitaletto, which registered the 2.3%). More specifically, the most relevant values concern Cassano d'Adda (25.4%), Antegnate (26.4%) and Fara Olivana con Sola (27.5%): these values depend on the fact that the highway passes through the mentioned municipalities from side to side and not only partially as in other cases. Moreover, in the case of Fara Olivana con Sola the high value of soil consumption is also determined by the presence in the territory of the municipality, which is the smallest in terms of extension among all those considered, of a toll booth with the relative road junctions.

Considering now the LcI, the contribution is much lower (note that consistent parts of the new infrastructures fall outside the administrative limits of the municipalities crossed by the highway), but surpasses the 5% in 9 municipalities. A peak occurs in Roncadelle, where the linear Isc represents the 20% of the total soil consumption in the city for the period 2007-2018: as a matter of fact, in this municipality lots of intervention concerning the requalification of the South Beltway in Brescia had place, as part of the connecting and compensatory interventions of the Brebemi.

Regarding the AcI, the percentages appear more critical: just in 8 municipalities, almost the 30% of the total amount, this contribution is lower than the 25% of the total soil consumption registered in the territories; 11 cases have values between the 25 and 40%; finally, in 8 municipalities the values exceed the 40%, with peaks higher than the 60% for Antegnate and Fara Olivana con Sola.

The situation is even more alarming when we consider the contribution of the whole soil consumption due to the Brebemi highway (defined as Total-consumption of the Brebemi Index – TcI_B) (Fig.11): 19 municipalities, more than the 70%, reach values higher than the 40%, and 8 of them surpass the 60%. Again, the highest values are in the municipalities of Fara Olivana con Sola, 92%, and Antegnate, 88%: in other words, almost the totality of the soil consumption occurred in these municipalities in the period 2007-2018 was made by the Brebemi itself, by the connected infrastructures and in a 1km area from the highway border.

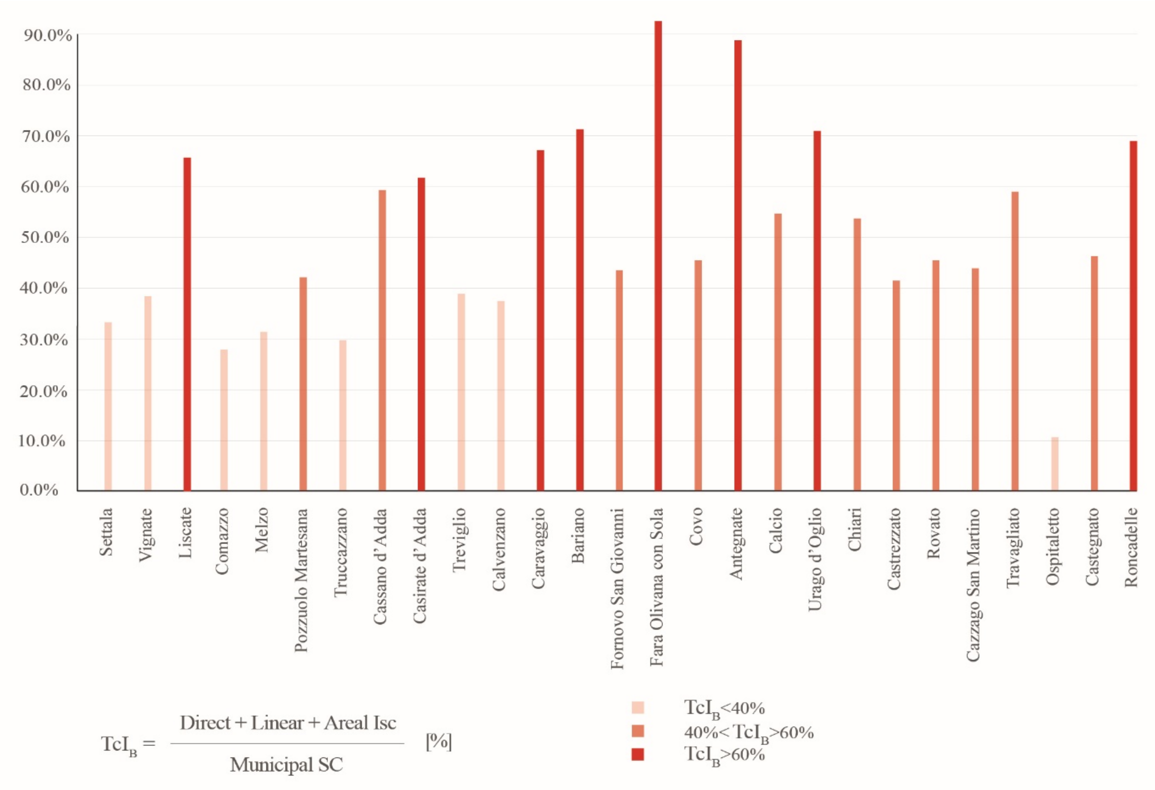

Fig.11 Incidence coefficient of soil consumption (direct + inducted) in the period 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

Given the higher contribution of the areal inducted soil consumption and since it is not possible to compare the direct and linear soil consumption in 2007-2018 to 1999-2007 (the infrastructures had not been built yet), Figure 12 reports the comparison between the AcI pre-Brebemi (period 1999-2007) and post-Brebemi (period 2007-2018). Except for few cases (Cassano d'Adda, Cazzago San Martino, Pozzuolo Martesana and Truccazzano), all the municipalities register a consistent increase in value of AcI: 11 municipalities show a more than threefold increase and among these 5 municipalities register more than five times the value of 1999-2007. Finally, three municipalities reach values at least 70 times higher than those of the previous period: more specifically, Comazzo passes from a percentage of 0.24% in 1999-2007, to a 18.70% in 2007-2018 (78 times higher); Calcio switches from 0.18% to 30.92% (168.8 times higher); Urago d'Oglio registers a 43.27% in 2007-2018 compared to the 0.16% in 1999-2007 (270.3 time higher).

In sum, we can state that the soil consumption in the 1km buffer zone has increased in the period post-Brebemi in almost all the municipalities crossed (except for four cases), passing from a total soil consumption of 225 ha in the period 1999-2007 to a value of 650 ha in the period 2007-2018 (Fig.13). A further reflection can be done by comparing areal induced soil consumption data in different buffer zones: 0-500m (already taken as Areal Isc), 500-1000m, 1000-1500m, 1500-2000m, 2000-2500m[11] (all are considered for each side of the highway). Such analysis makes us to better understand and quantify the Brebemi impact on land-use changes of the surrounding territory. The results are shown in Tab.4 and Fig.14, where it is evident how the soil consumption in the pre-Brebemi period is highest in the buffer area 1,000-1,500m. On the contrary, the lowest values are in the buffer areas 0-500m and 2,000-2,500m. This data is probably due to the distribution of the urbanized area.

[11] First results of this analysis were carried out by Fornasari, 2023.

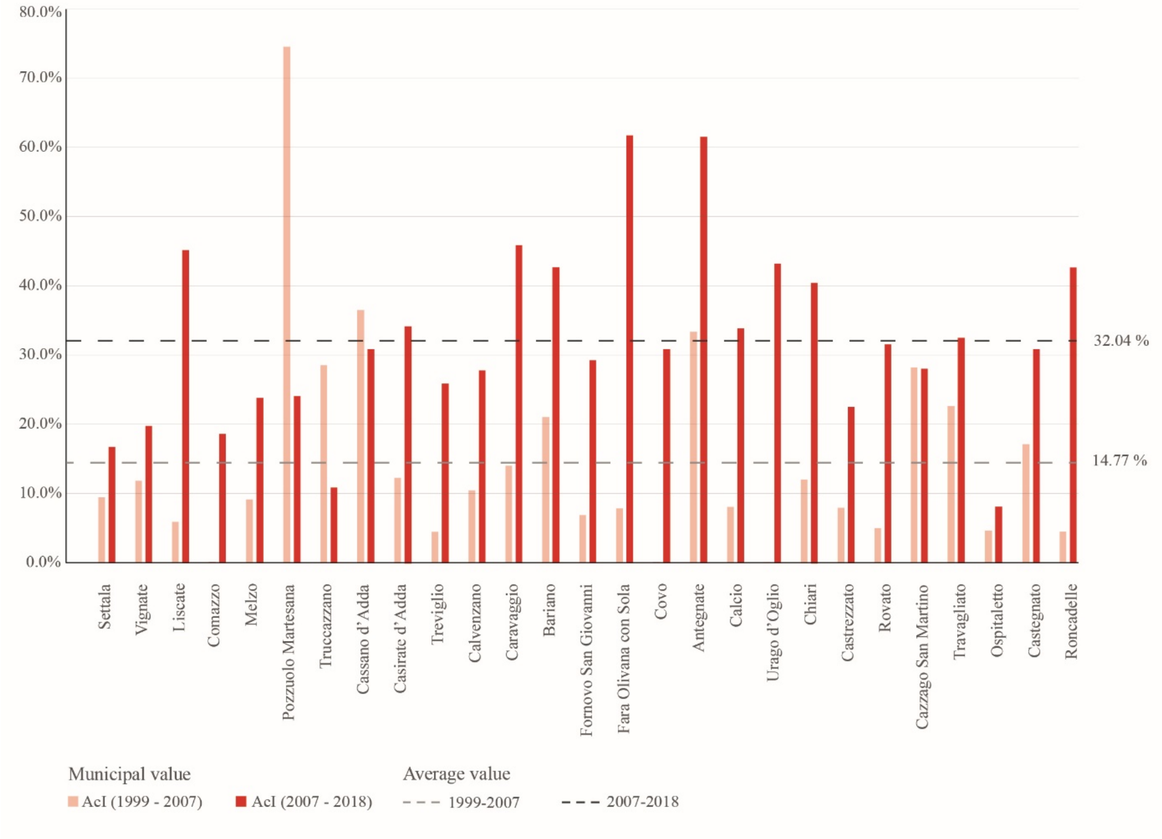

Fig.12 Incidence coefficient of ~~the~~ areal inducted soil consumption in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

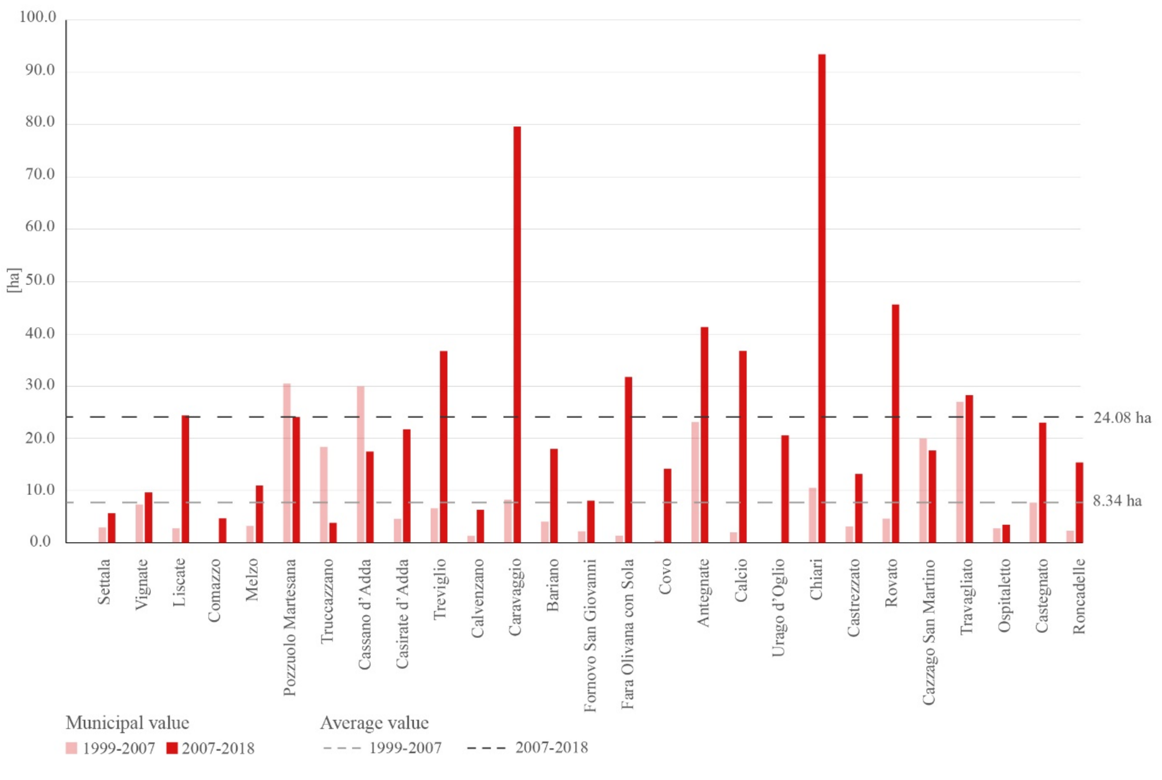

Fig.13 Areal induced soil consumption in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

As a matter of fact, in 1999, starting moment of the analysis, the coefficient of urbanized area for each buffer was quite different, varying from the 22% in the buffer of 1000-1500m (the highest value) to less than 10% in the buffer of 0-500m (the lowest one). The situation changes after the realization of the highway, in the post-Brebemi period, when the peak of soil consumption is in the buffer area 0-500m (note that in this buffer the value of the Dsc is always excluded). Such results confirm what has emerged from the previous analysis, namely that the Brebemi highway has strongly affected land-uses in its surroundings, by determining a huge inducted soil consumption.
However, it is also possible that in the future the Brebemi effect can propagate to greater distances from the highway as the closest buffers become saturated and the availability of building land decreases.

Buffer	Soil consumption [ha]		
	Pre-Brebemi (1999-2007)	Post-Brebemi (2007-2018)	Variation
0 - 500 m (Areal Isc)	225	650	195%
500 – 1,000 m	286	273	-5%
1,000 – 1,500 m	296	204	-31%
1,500 – 2,000 m	246	192	-22%
2,000 – 2,500 m	221	151	-32%

Tab.4 Values of soil consumption pre and post Brebemi for different buffer areas. The data do not include the values of the Brebemi highway and of the inducted infrastructures

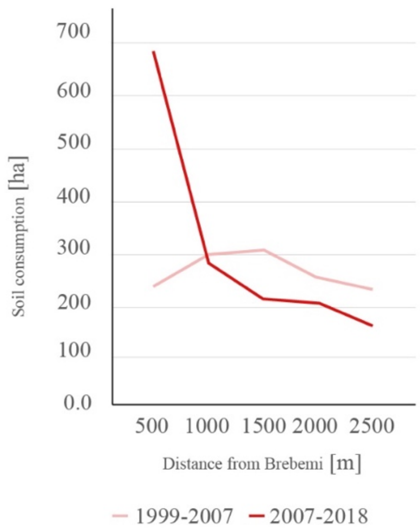

Fig.14 Areal induced soil consumption related to the distance from the Brebemi highway in the periods 1999-2007 and 2007-2018. The data do not include the values of the Brebemi highway and of the inducted infrastructures

6. Conclusion: monitoring and reducing direct and inducted soil sealing due to new road infrastructure

The paper has discussed the impacts on land transformations derived from the construction of a new highway, by focusing on the quantification of soil consumption. The analysis tackles two different kinds of transformations: one directly generated by the infrastructure itself (the natural soil lost due to the realization of the road); another inducted by the infrastructure (e.g. other new inducted infrastructures connected to the new road or new urbanized areas). The case study of the Brebemi highway in Italy was selected as a valid case to examine these double typologies of impacts on land transformations. The analysis has been carried out in order to quantify the impacts on soil consumption caused by the infrastructure itself (defined as direct soil consumption), but also caused by the new infrastructures connected to the highway (defined as linear inducted soil consumption) and by new urbanized areas located in a buffer zone of 500m from each side of the highway (defined as areal inducted soil consumption). The results have demonstrated how the Brebemi has been a decisive lever for the land transformations: not only for its direct impact, but mainly for the inducted works. The discussion about the inducted part is one of the main results of this analysis, since it demonstrates that the construction of a new infrastructure, especially of national or over-local level, needs to be considered in its whole dimension of environmental impacts. This means acknowledging that the effects of highway construction will extend across both space and time, spanning different jurisdictions both horizontally (involving multiple municipalities, provinces, or even regions) and vertically. Indeed, for such major infrastructure projects, the approval process typically begins at the national level and subsequently involves lower levels of governance. For its approval, the Brebemi highway project by-passed the typical Environmental Impact Assessment (EIA) process in favor of a faster, more streamlined evaluation under the so-called "Obiettivo Law" (Law No. 443/2001). This acceleration, typical of large-scale and strategic public works or infrastructures, often raises justified criticism, particularly because, while they could arise significant economic and social benefits, they also tend to cause the most widespread and unpredictable environmental impacts on a large scale. The findings of this study should highlight the need for a more in-depth evaluation of highway impacts, with particular emphasis on assessing previsions on soil consumption and recognizing induced soil consumption as a potential effect. Concurrently, within planning instruments, previsions on land transformations (not only due to the infrastructure itself but also to induced soil consumption) must already today be subject to Strategic Environmental Assessment (SEA) to evaluate environmental impacts. However, at the planning stage territorial authorities should broaden and strengthen this assessment process, which is neither uniform nor consistently effective in evaluating and measuring soil consumption (Moscarelli and Pileri, 2020). This should apply both to municipal master plans, which are in most of the cases responsible for land cover transformations, and to larger territorial areas, such as provinces, which can provide a broader and cumulative perspective on the spatial effects of a single infrastructure. The correlation between the Brebemi and what has been defined as inducted transformations, linear and areal, is at the same time an added value of the analysis and a critical point of it. As a matter of fact, it not completely demonstrable that inducted transformations, especially the areal ones, were provoked by the new highway. This can be assumed as a limit of the analysis, even if the decision of considering just a 1km buffer zone can in part reduce such weakness. Moreover, the indicators presented in the discussion, especially those including the comparison between the period pre and post-Brebemi, describe almost in all the cases the high incidence of the Brebemi and, thus, its reasonable incidence in the inducted transformations of the soil. Such data are in part confirmed by the local plans, which in 12 cases (44.4% of the total municipalities crossed) explicitly declare that the new urban transformations are strongly influenced and fostered by the presence of the Brebemi[12] (Giuliani, 2023). Nevertheless, it would be interesting to deepen the analysis of the correlation between the infrastructure and other inducted works, also considering the scientific debate on the road-effect zone. In this sense, it would be necessary to carry out a more detailed study on the land cover transformations in a wider part of territory, e.g. by identifying different buffer zones. Another point that should be analyzed more deeply concerns the typology of transformations more spread in the buffer zone, whether they are productive, logistic, commercial or residential: in this way it would be possible to enrich the correlation between new infrastructures and transformations of the territory. In addition, future studies should be aimed at assessing land consumption

[12] This regards, in particular, Bariano (Municipality of Bariano, 2013), Calcio (Municipality of Calcio, 2017), Calvenzano (Municipality of Calvenzano, 2011), Caravaggio (Municipality of Caravaggio, 2013), Castrezzato (Municipality of Castrezzato, 2012), Cazzago San Martino (Cazzago San Martino, 2007), Chiari (Municipality of Chiari, 2009), Fornovo San Giovanni (Municipality of Fornovo San Giovanni, 2011), Liscate (Municipality of Liscate, 2011), Pozzuolo Martesana (Municipality of Pozzuolo Martesana, 2014), Settala (Municipality of Settala, 2011), Travagliato (Municipality of Travagliato, 2011).

after 2018 (and thus not registered by the DUSAF version considered) still connected to the construction of the highway, a link that is likely and confirmed by local plans: for example, the municipality of Chiari registered a consistent logistical expansion in 2021 declaredly connected to the presence of the Brebemi in the territory (Giuliani, 2023). Finally, it could be useful also to compare this case with other relevant infrastructures, in order to verify whether the land transformations trends appear similar or not.

Author contributions

The authors have shared the concept of the paper. R.M. has written the paragraphs 1,2 and 5. M.G. has written the paragraphs 3,4 and 6. The part written by R.M. is a result of the SPADES project, funded by the European Union (Grant Agreement No. 101146122). Views and opinions expressed are, however, those of the author only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor REA can be held responsible for them.

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Image Sources

Fig.1 – 14: own elaborations by authors

Tab. 1 – 4: own elaborations by authors

Author's profile

Rossella Moscarelli

PhD in Urban Planning, Design and Policies, and Assistant Professor at Politecnico di Milano, Department of Architecture and Urban Studies. Her research focuses on sustainable mobility, soil sealing analysis and on their integration in urban planning and public policies.

Marialaura Giuliani

Graduated in Environmental Engineering in 2023 at Politecnico of Milano, with a master thesis titled "Consumi di suolo diretti e indotti nelle opere autostradali. Il caso A35 Brebemi". She is currently a phD student in "Civil and Environmental Engineering, International cooperation and Mathematics" at the University of Brescia. Her research interests include soil sealing effects and ecosystem services' evaluation and valorisation.