

Temporal and spatial patterns of the Sealed-to-Artificial area Ratio in European urban areas

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ABSTRACT

Land take is primarily driven by urbanisation and infrastructure development and is closely linked to soil sealing, which involves covering soil with impervious materials. Over recent decades, both processes have steadily increased in European urban areas, significantly impacting ecosystem services. To stop these processes, the European Commission has set two distinct targets: "no net land take" and "no net soil sealing". To examine the relationship between the two processes, we introduce the Sealed-to-Artificial area Ratio (SAR), a novel indicator defined as the ratio between sealed areas and artificial areas in a certain region. We computed SAR for 661 Functional Urban Areas (FUAs) in the 27 countries of the European Union plus the UK, and its change between 2012 and 2018. Two hypotheses were tested: (1) SAR tends to decrease in FUAs with predominant agricultural land cover, as opposed to artificial; and (2) SAR tends to increase as urban form becomes more compact, as opposed to sprawling. Results show a general decrease in SAR (median of -0.36), indicating a possible trend toward lower-intensity urban development. However, regional variations emerge, with the UK-Ireland showing a greater decrease and the Southern region a smaller reduction. As expected, SAR increased in FUAs with a high share of artificial land cover and a tendency towards a more compact urban form, while those with larger availability of agricultural land and a sprawling development showed the opposite trend. The proposed indicators can be used to support urban planning and local policies to achieve European targets.

1. Introduction

Land take can be defined as the conversion of agricultural, forest, and other (semi-)natural lands to urban and other artificial land uses (EEA, 2006). In combination with climate change, land take is among the main causes of biodiversity decline through habitat loss, fragmentation, and indirect degradation (Geneletti et al., 2017; Newbold et al., 2015; Urban et al., 2024). Land-use changes associated with land take significantly contribute to CO₂ emissions (Hutyra et al., 2011; Sallustio et al., 2015; Seto et al., 2012). In addition, urban areas are often located on land that is suitable for crop production (Gardi et al., 2015), and the impact of land take on food production capacity is projected to increase in the near future (van Vliet et al., 2017). Land take trends in recent decades, and their decoupling from population growth in several parts of the world, have raised increasing concerns (Li et al., 2022), despite artificial areas representing only a small fraction of the global land area (Liu et al., 2014).

Land take is closely linked to soil sealing, which occurs when soil is

covered by impervious materials, like concrete or asphalt (EC, 2011a). The sealed layers disrupt the connection between soil and atmosphere, resulting in the loss of soil functions and related ecosystem services (Tóth et al., 2022). The impacts are especially strong in urban areas, where the high share of sealed soil may contribute, among others, to exacerbate flood risk (Du et al., 2015) and the urban heat island effect (Fokaides et al., 2016). Moreover, soil is the singular most biodiverse habitat on Earth (Anthony et al., 2023) and the loss of soil biodiversity is likely to produce significant effects on human health (Sun et al., 2023). For these reasons, addressing soil sealing has become a top priority for sustainable urban development (Naumann et al., 2019).

The negative consequences of land take and soil sealing have triggered policy responses at multiple levels. The European Union (EU), one of the regions where land take and soil sealing keep increasing despite outpace population growth, has been at the forefront. In 2011, the European Commission launched a "Roadmap to a Resource Efficient Europe" including the target of "no net land take" to be achieved by 2050 (EC, 2011b). Ten years later, acknowledging the specific

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challenges related to soil health, the EU Mission “A Soil Deal for Europe” included among its specific objectives to achieve “no net soil sealing” by 2050 (EC, 2021). Both targets refer to “net changes”, implying the possibility of offsetting land take and soil sealing with compensation measures. These measures include land re-naturalisation interventions (i.e., the conversion of artificial land back to natural or semi-natural uses) (EEA, 2021) and de-sealing interventions (i.e., the removal of the sealed layers from surfaces) (EC, 2011a).

Both the “no net land take” and the “no net soil sealing” targets are aimed at reducing the negative impacts of urbanisation on land, hence synergies can be expected in their implementation. However, given that the relationship between land take and soil sealing varies across contexts (Decoville and Feltgen, 2023), the extent to which different strategies and actions contribute to the two targets is unclear. In Europe, where land take and soil sealing are routinely monitored (EEA, 2021; EEA, 2023), previous studies have highlighted the spatial variability of the two processes across the continent (Cortinovis et al., 2019; Salvati, 2014; Salvati et al., 2018; Tóth et al., 2022). However, partly due to the existence of numerous and varying definitions for these two processes (Decoville and Schneider, 2016; Marquard et al., 2020), land take and soil sealing have rarely been analysed together.

A few studies investigated the share of sealed soil within artificial areas. For example, Decoville and Feltgen (2023) analysed the city centres of 100 large European cities in 2018 and found values ranging from 31.5% to 72.6%, with an increase from north to south. Similar analyses were conducted in other contexts and at different scales, including a sample of cities in Poland (Kudas et al., 2024), Portuguese municipalities within the Porto Metropolitan area (Nicolau and Condessa, 2022), and industrial and commercial areas in northern Italy (Salata et al., 2019). Overall, these studies demonstrate that the share of sealed soil in artificial areas varies considerably across contexts, but none of them has provided a comprehensive overview at the European scale. Moreover, no analysis so far has included the temporal dimension involved in land take and soil sealing processes, which limited the understanding of factors that could explain the observed variability.

The objective of this paper is to address this gap by analysing the temporal evolution of the ratio between sealed soil and artificial area in European urban areas and testing hypotheses on two factors - landscape composition and urban form - potentially affecting such ratio. To link soil sealing and land take, we introduce an indicator, the Sealed-to-Artificial area Ratio (SAR), which quantifies the ratio between area of sealed soil and artificial area, and calculate its change over the period 2012–2018 for 661 urban areas in Europe. The rationale for the selection of the factors and the formulation of the associated hypotheses is explained next.

Landscape composition refers to the combination of land uses in the landscape, while urban form refers to the spatial characteristics of urban development. Most of land take affects agricultural land (Barbosa et al., 2017; Gardi et al., 2015) due to a combination of reasons that include proximity to existing settlements, hence greater demand compared to more remote places; higher suitability to urban development and ease of conversion compared e.g. to forest land; and lower planning restrictions compared to (semi-)natural land (Colsaet et al., 2018). In Europe, the most common type of urban expansion in such areas is the construction of low-density residential suburbs, characterised by a population density and an average share of sealed soil significantly lower than those of core cities (EEA et al., 2022; Zambon et al., 2017). On the contrary, strategies to reduce land take have emphasised the need to reduce sprawling development and promote compact urban growth through infill and densification, thus focusing on rebuilding within existing city boundaries rather than expanding outward (Decoville and Feltgen, 2023). By promoting medium-density living (Orsi, 2023) and prioritising vertical growth and the increase in building volumes (Rodrigo-Comino and Ermini, 2021; Romano et al., 2023), such strategies encourage the concentration of population and activities, hence a more efficient use of

land (Cortinovis et al., 2022).

Based on these observations, we formulated two hypotheses, and tested through the methods described in the next section:

1. The Sealed-to-Artificial area Ratio tends to decrease in areas where the landscape composition is predominantly agricultural, while the opposite is expected in predominantly artificial landscapes.
2. The Sealed-to-Artificial area Ratio tends to increase when the urban form becomes more compact, while the contrary is expected when sprawl prevails.

The remainder of the article is structured as follows. Section 2 describes the methods, sample, and data used for the analyses. Section 3 presents the trends and spatial patterns of the Sealed-to-Artificial area Ratio indicator, and the results related to the two hypotheses. Section 4 discusses the results and outlines the limitations of the study. Finally, Section 5 draws some general conclusions.

2. Materials and methods

2.1. Sample of cities and data set

The analysis focused on all 661 Functional Urban Areas (FUAs) within the 27 EU countries and the United Kingdom (UK). FUAs include both core cities and their surrounding commuting zones, thus providing a suitable scale for analysing spatial phenomena related to urban growth (Busłowska and Marcinkiewicz, 2023; Schiavina et al., 2022). Overall, the selected FUAs cover a total area of around 1 Mkm², equal to 22.4% of the total surface of the 28 countries. The analysis covers the period between 2012 and 2018, the most recent years for which comparable data is available at the EU scale (only the Urban Atlas dataset is also available for 2021).

In particular, we estimated sealed areas using the Imperviousness Density Map (IDM) provided by the Copernicus Programme of the EU for the years 2012 and 2018 at a resolution of 1 Km. This dataset, released in 2024, includes a correction of the comparability issues related to the original maps at 10 m resolution (EEA et al., 2024). The calculation of artificial areas is based on the Urban Atlas dataset for both 2012 and 2018.

2.2. Computation of the Sealed-to-Artificial area Ratio (SAR)

We quantified the area of sealed soil within each FUA by summing the contributions of all individual pixels. The contribution of edge pixels was weighted according to the portion of the pixel that falls within the FUA. We calculated the artificial area by summing the areas of all artificial surfaces as defined in the legend of the Urban Atlas (codes 11100–14200, more details in the [Supplementary Material](#)). Green urban areas (code 14100) were classified as artificial areas due to their high spatial heterogeneity and the frequent presence of compacted soils and significant anthropogenic pressures. For this reason, they were included in the artificial areas to avoid underestimating SAR values. For example, Tóth (2012) also classify green urban areas as artificial surfaces. We then computed SAR for a specific year as the ratio of the area of sealed soil to the artificial area within a FUA (Eq. 1). SAR was calculated for each FUA in the sample in the two reference years 2012 and 2018.

$$SAR = (\text{Area of sealed soil}) / (\text{Artificial Area}) \quad [\text{km}^2 / \text{km}^2] \quad (1)$$

Additionally, we assessed the change in this ratio over the analysed period (Eq. 2), which we call ΔSAR . Descriptive statistics were used to analyse the distribution of SAR and ΔSAR in the sample of FUAs.

$$\Delta SAR = (SAR_{2018} - SAR_{2012}) * 100 \quad (2)$$

In addition, we calculated two indicators, Net Land Take (NLT) and

Net Soil Sealing (NSS), for the period between 2012 and 2018. NLT (km²) measures the difference between land taken by urban expansion and land that has been re-naturalised (EC, 2011b) and was calculated as the difference between the artificial area in 2018 and 2012. NSS (km²) measures the difference between new soil sealing (such as roads and buildings) and soil de-sealing, and it was assessed as the difference between the area of sealed soil in 2018 and in 2012.

To identify spatial patterns of SAR and Δ SAR, we examined how their values varied spatially across different countries (listed in the [Supplementary Material](#)) and regions. At the regional level, we adopted the classification used by [Lagarias and Prastacos \(2021\)](#), which distinguishes five regions in Europe: UK-Ireland, Northern, Central, Southern, and Eastern Europe. To determine whether SAR and Δ SAR significantly differ across various spatial classifications, we conducted a series of univariate analyses of variance (ANOVA). When ANOVA revealed statistically significant differences among groups, we used Tukey's post hoc tests to determine which specific pairs of countries and regions had significantly different indicator values. All statistical analyses in this study were conducted using R ([R Core Team, 2024](#)) and Jamovi software.

2.3. Analysis of the relationship between SAR and landscape composition

To test the first hypothesis regarding landscape composition, we first categorised the FUAs using the landscape mosaic classification developed by [Vogt et al. \(2024\)](#). The latter is a tripolar classification of landscape composition that considers three predominant land cover types: agricultural, natural, and developed areas (which we estimated based on Corine level 1 for 2012). The classification comprises 19 classes resulting from a partitioning of the space based on three threshold values (10%, 60%, 90%) that indicate the share of FUA's area covered by each land cover type ([Table 1](#)). Once each FUA was assigned to the corresponding landscape composition class, we explored whether SAR and Δ SAR differed across the various classes using ANOVA and the Tukey's post hoc test.

2.4. Analysis of the relationship between SAR and urban form

To test the second hypothesis, we selected three landscape metrics that describe urban form and examined their relationship with Δ SAR.

Table 1

Classes of landscape composition (based on [Vogt et al. \(2024\)](#)). In the class code, lowercase letters indicate land cover types covering between 10% and 60% of the FUA area, while uppercase letters indicate types covering more than 60%. A, a = agricultural; N, n = natural; D, d = developed (artificial).

Class code	Area threshold of land cover types	Number of FUAs
A	agricultural > 60%, natural < 10%, developed < 10%	31
N	natural > 60%, agricultural < 10%, developed < 10%	7
Ad	60% < agricultural < 90%, 10% < d < 40%, natural < 10%	85
An	60% < agricultural < 90%, 10% < natural < 40%, developed < 10%	173
Da	60% < developed < 90%, 10% < agricultural < 40%, natural < 10%	2
Na	60% < natural < 90%, 10% < agricultural < 40%, developed < 10%	53
Nd	60% < natural < 90%, 10% < developed < 40%, agricultural < 10%	6
ad	40% < agricultural < 60%, 40% < developed < 60%, natural < 10%	47
an	40% < agricultural < 60%, 40% < natural < 60%, developed < 10%	238
dn	40% < developed < 60%, 40% < natural < 60%, agricultural < 10%	19

The metrics measure different aspects of compactness vs sprawl: shape irregularity, patch aggregation, and patch dispersion. Shape irregularity is measured through the Edge Density (ED), i.e., the total length of urban edges per unit of urban area. ED increases as the shape of urban areas becomes more irregular ([Schwarz, 2010](#); [Seto and Fragkias, 2005](#); [Reis et al., 2016](#)). Patch aggregation is measured through the Percentage of Like Adjacencies (PLADJ), i.e., the proportion of cell adjacencies involving the same class. PLADJ increases as urban areas become more aggregated ([Schwarz, 2010](#); [Triantakoustantis and Stathakis, 2015](#)). Patch dispersion is measured through the Nearest Neighbor Index, i.e., the ratio between the observed mean distance between neighbouring patches of the same class and the average distance in a theoretical random distribution. Values lower than 1 indicate clustering, while values greater than 1 suggest dispersion ([Barbini et al., 1996](#); [Ojima and Hogan, 2009](#)). A more compact urban form is expected to be characterised by lower values of ED, higher values of PLADJ, and lower values of NNI compared to a sprawling form ([Ojima and Hogan, 2009](#); [Seto and Fragkias, 2005](#); [Triantakoustantis and Stathakis, 2015](#)). Therefore, a reduction of ED and NNI and an increase in PLADJ indicate that urban areas are moving towards a more compact urban form, as opposed to a more sprawling form ([Ojima and Hogan, 2009](#); [Seto and Fragkias, 2005](#); [Triantakoustantis and Stathakis, 2015](#)).

To calculate the selected landscape metrics, we first converted the Urban Atlas maps of the FUAs into binary raster maps of urban and non-urban areas at 10-meter resolution. ED and PLADJ were calculated using Fragstats4.3 ([McGarigal et al., 2012](#)). The NNI was calculated in QGIS using the Designer Builder, by polygonising urban patches, defining patch centroids, and performing nearest neighbor analysis. We then assessed the variation of landscape metrics in the analysed period between 2012 and 2018. To explore the correlation between Δ SAR and the variation of landscape metrics, we used the Spearman coefficient (ρ).

3. Results

3.1. Spatial patterns of SAR

In 2012, the median SAR in the FUAs sample is 0.44. SAR values range from 0.21 (in Kaposvár, Hungary) to 0.77 (in Battipaglia, Italy) ([Fig. 1a](#)). In the period between 2012 and 2018, SAR shows a general reduction in the sample, with a median Δ SAR value of -0.36 . Δ SAR values range from -5.0 to -2.5 , with 618 FUAs exhibiting negative values and only 43 showing positive values ([Fig. 1b](#)). A total of 241 have Δ SAR values between -0.75 and -0.25 , and 111 FUAs have Δ SAR values close to zero within the range of -0.25 to -0.25 . The only two values falling outside the range from -5.0 to -2.5 are -9.24 in Battipaglia, located in southern Italy, and 3.03 in Arrecife, in Las Palmas Spain ([Fig. 2](#)). FUAs at the lower end of Δ SAR range (negative values) are primarily located in the southern areas of the United Kingdom, Belgium, Romania, and western Poland. In contrast, FUAs at the higher end of the range (positive values) are predominantly situated in Spain, southern Italy, Slovakia and Poland.

The value of Δ SAR is linked to the ratio between NSS and NLT during the analysed period ([Fig. 3](#)). All urban areas (61) with a ratio between NSS and NLT above 0.75 show a positive Δ SAR (area A in [Fig. 3](#)). On the contrary, where the ratio between NSS and NLT is lower than 0.25, Δ SAR is always negative (362 FUAs – area C in [Fig. 3](#)). NSS/NLT values between 0.25 and 0.75 (area B) correspond to both positive and negative Δ SAR values. However, urban areas with especially high values of NLT, such as Paris and Warszawa, have a negative Δ SAR, except for Dublin, where NSS values were also significantly higher than the average of the sample. Negative values of Δ SAR are also found in 4 FUAs in Italy characterised by negative NSS and positive NLT. Conversely, Δ SAR is positive in all urban areas with negative NLT (20 FUAs mainly located in Spain including Puerto de la Cruz, the only one where both NSS and NLT are negative). SAR, Δ SAR, NSS and NLT data are in the [Supplementary Material](#).

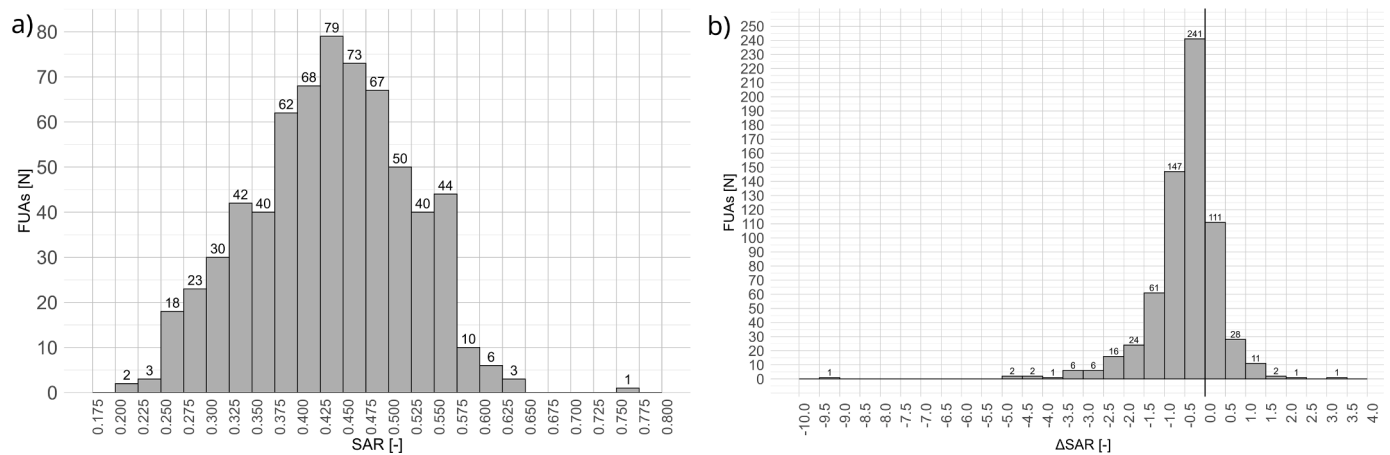


Fig. 1. a) Distribution of SAR across European FUAs in 2012 and b) Distribution of Δ SAR across European FUAs in 2012–2018.

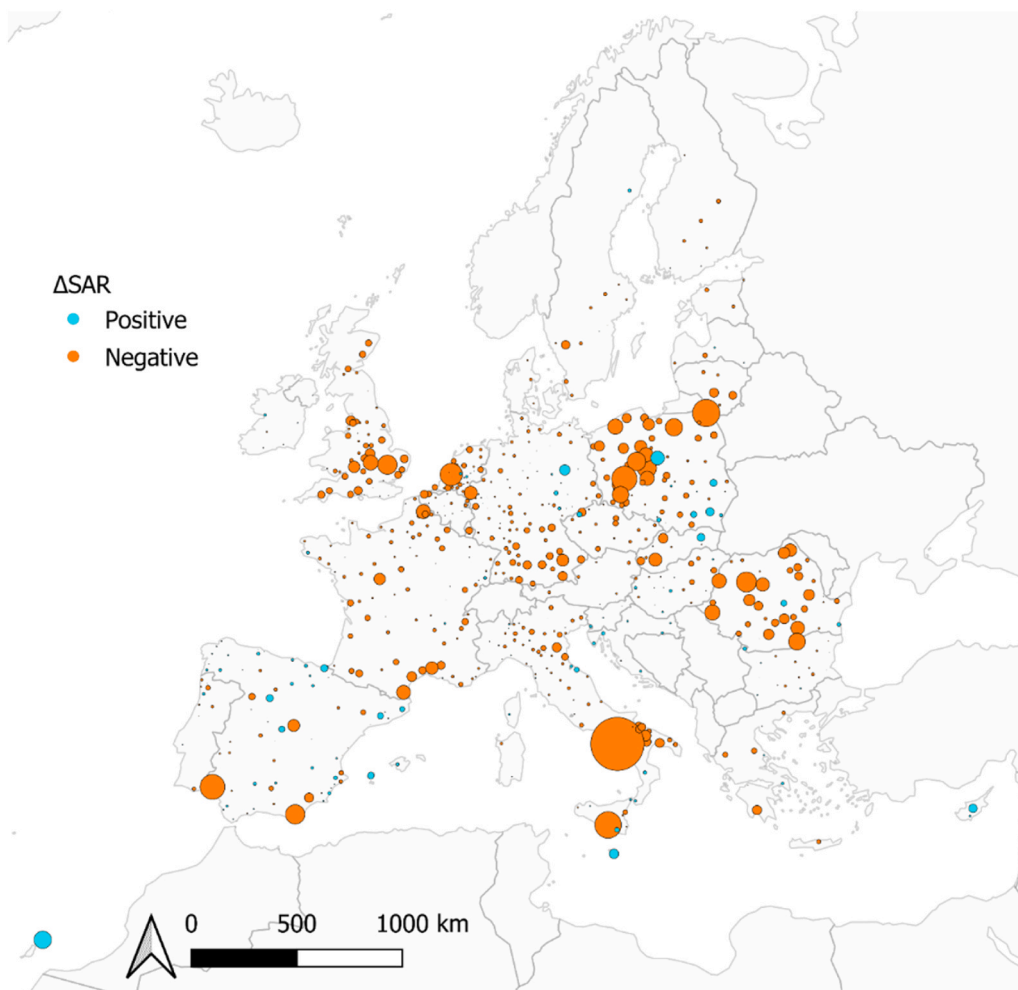


Fig. 2. Map of Δ SAR values for each FUA, with circle size proportional to the value of Δ SAR.

In 2012, the range of SAR values of urban areas in the Central, Southern, and UK-Ireland regions are similar, while urban areas in the Eastern and especially in the Northern regions show lower SAR values (Fig. 4a). Countries within Northern Europe likewise have lower median SR values than those in the remaining regions (Fig. 4b). However, Δ SAR for this region (median of -0.4) is comparable to the median Δ SAR observed in Central and Eastern Europe over the study period (Fig. 4c). The UK-Ireland region instead shows the most significant decrease in

SAR (median of -0.7), while the Southern region is where the reduction in the value of the indicator was on average the smallest. At the country scale, median values of Δ SAR are consistent with those observed at the regional level (in Fig. 4d).

The values of the indicator in 2012 and their changes during the analysed period do not show any clear relationship. Although in 2012 Central Europe has the highest SAR values (median of 0.47), its median Δ SAR between 2012 and 2018 is the same as in Northern Europe.

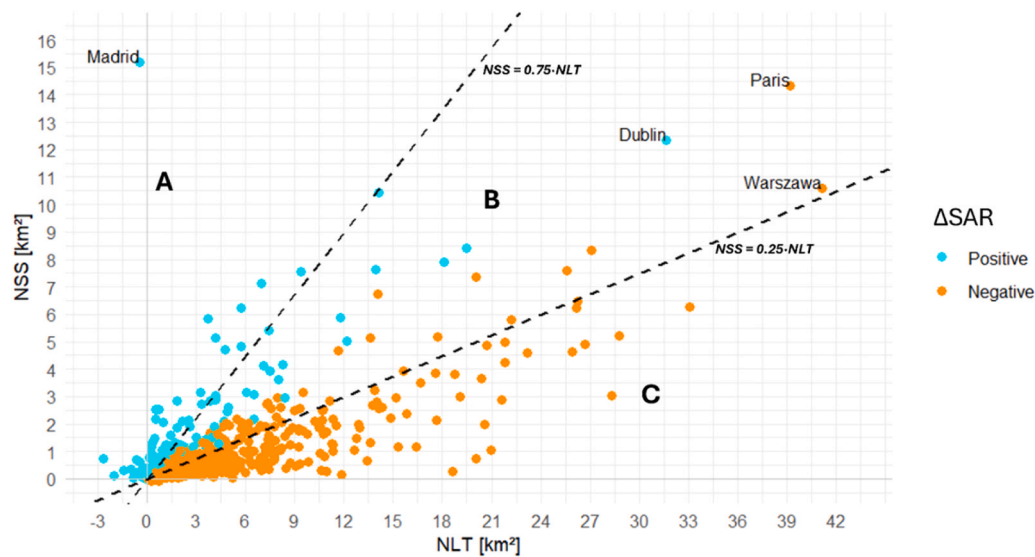


Fig. 3. Net Land Take (NLT) and Net Soil Sealing (NSS) for each FUAs. In the region “A”, delimited by the line $NSS = 0.75 \cdot NLT$, all FUAs have positive ΔSAR values. In the region “C”, delimited by the line $NSS = 0.25 \cdot NLT$, all FUAs have negative ΔSAR values. The region “B” includes FUAs with either positive or negative ΔSAR values.

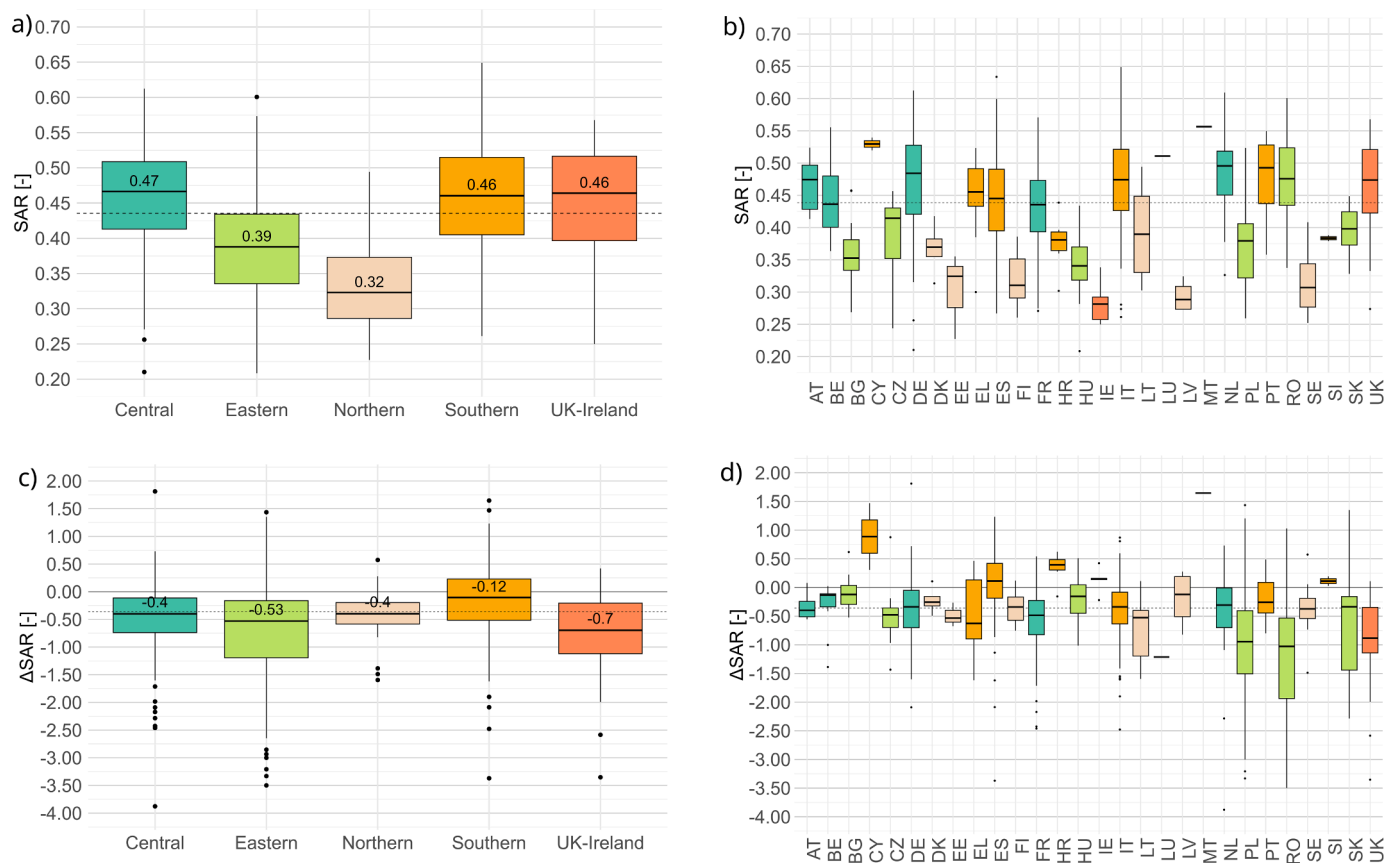


Fig. 4. Spatial distribution of SAR and its temporal variation (ΔSAR) a) SAR by region b) SAR by country; c) ΔSAR by region and d) ΔSAR by country (the countries corresponding to each code are listed in [Supplementary Material](#)).

Southern Europe and the UK–Ireland have the same median SAR values in 2012, but the most extreme median values of ΔSAR (−0.12 and −0.7 respectively). It is also noteworthy that median ΔSAR values for certain countries within these regions (Fig. 4d) differ from the regional median values (Fig. 4c). For example, in Southern Europe, Italy and Portugal have a negative median ΔSAR , whereas Cyprus and Croatia show a

positive value of the indicator. In the UK–Ireland region, Ireland has a positive median ΔSAR , whereas the United Kingdom is much below zero. The ANOVA statistical analysis confirms differences among regions and countries. However, the Tukey Test results indicate that only specific group comparisons can be considered statistically significant. The statistically significant differences are observed mainly for the SAR

indicator across regions, rather than for Δ SAR and across countries (see [Supplementary Material](#)).

3.2. Variability of SAR across landscape composition and urban form

FUAs with a primarily artificial landscape composition (*Da*) show the highest median SAR in 2012 ([Fig. 5a](#)). Gouda in the Netherlands and Portsmouth in the United Kingdom, the only two FUAs in the class, have SAR values of 0.61 and 0.57, respectively, placing them at the upper end of the range. In contrast, FUAs where natural areas prevail tend to show lower SAR values compared to FUAs in other classes, with the class characterised by more than 80% of natural areas (*N*) showing the lowest median SAR. The values of SAR in FUAs with a significant presence of agricultural areas are influenced by the presence of other land cover types. Those with a higher proportion of artificial areas (*ad* and *Ad*) have higher-than-average SAR values, whereas FUAs where agricultural areas are associated with natural landscapes (*An*) tend to show lower SAR values.

At the same time, FUAs that are primarily agricultural show lower Δ SAR values compared to other classes ([Fig. 5b](#)). In particular, Δ SAR between 2012 and 2018 in the FUAs characterised by a predominantly agricultural landscape composition (*A*, *Ad*, and *An*) is negative, with median values ranging from -0.42 to -0.67 . Conversely, FUAs with a dominant (*Da*) or significant share of artificial areas (*dn*) have the highest Δ SAR values, close to zero in both cases. FUAs with a prevalent natural land cover (*N*, *Nd*, *Na*) stand in between, with median values for the classes ranging between -0.26 and -0.04 . Also in this case, the ANOVA statistical analysis confirms the differences among the landscape composition classes, but the results from the Tukey Test indicate that only certain comparisons are statistically significant, for example *An* and *dn* (in [Supplementary Material](#)).

Considering the selected landscape metrics, changes in ED and PLADJ are negatively correlated, with all FUAs showing an increase in ED also showing a decrease in PLADJ, and vice versa. More than 50% of the FUAs show increased ED and decreased PLADJ, accompanied by a reduction in Δ SAR. Only about 8% of the FUAs in the sample, mainly located in Central and Southern Europe, show both a decrease in ED and an increase in Δ SAR, while around 5% show a contemporaneous decrease of both ED and Δ SAR. As shown in [Fig. 6a](#), the variation of ED between 2012 and 2018 (Δ ED) is strongly and inversely correlated with Δ SAR ($\rho = -0.623$), while the change in PLADJ (Δ PLADJ; [Figure S1](#) in the [Supplementary Material 1](#)) is strongly and directly correlated with Δ SAR ($\rho = 0.605$). The Nearest Neighbor Index (NNI) decreased between 2018 and 2012 in about 50% of the FUAs ([Fig. 6b](#)). No significant correlation between Δ NNI and Δ SAR can be observed.

4. Discussion

4.1. Added value of the proposed Sealed-to-Artificial area Ratio indicator

SAR indicator measures the ratio of sealed areas to artificial areas within a FUA for a specific year, while Δ SAR represents the variation in SAR indicator over a certain period. A ratio-based approach was adopted because sealed areas generally occupy a smaller extent than artificial areas, thereby improving comparability across different urban contexts. Moreover, expressing the indicator as a ratio facilitates the interpretation of temporal dynamics, allowing for a more consistent assessment of changes over time. In contrast to previous studies, which primarily focused either on land take or soil sealing as separate issues ([Cortinovis et al., 2019](#); [Salvati, 2014](#); [Salvati et al., 2018](#); [Tóth et al., 2022](#)), Δ SAR was specifically developed to integrate these two closely related processes. In particular, the indicator considers all types of transformations, including land take, renaturalisation, soil sealing, and de-sealing. It is important to note that both SAR and Δ SAR take into account all sealed surfaces and reflect all changes occurring within the FUA, not just those in artificial areas. Since the boundaries of the FUAs remain constant between 2012 and 2018, a positive Δ SAR indicates an increase in the ratio of sealed areas to artificial areas over time. This may be attributed to the development of new artificial areas that contain a higher proportion of sealed surfaces compared to pre-existing ones. Alternatively, a positive value may result from densification measures that increase the sealed surfaces within existing artificial areas, while the new ones that are established have a similar share of sealed areas as the existing ones. A further possibility is the expansion of sealed areas into non-artificial land. Nevertheless, [Tóth et al. \(2022\)](#) indicate that the increase in sealed surfaces predominantly occurs within artificial areas, with only a marginal contribution from other land-use classes. Therefore, positive Δ SAR values suggest a trend of intensified urban development at the urban scale.

By looking at the extreme values within the sample, we can observe contrasting urban development dynamics. Battipaglia (IT), which shows the lowest Δ SAR value (-9.24), experienced a significant increase between 2012 and 2018 in land-use conversion from mainly agricultural land and pastures to industrial and commercial uses. However, these newly developed areas showed only a limited increase in sealed surfaces, likely because the land-use change occurred during the study period, while full or substantial soil sealing had not yet taken place or was only partially completed, and may occur in subsequent years. In contrast, Arrecife (ES), located at the opposite end of the distribution with a Δ SAR value of 3.03, experienced very limited land-use conversion towards artificial areas. Nevertheless, a substantial increase in sealed surfaces

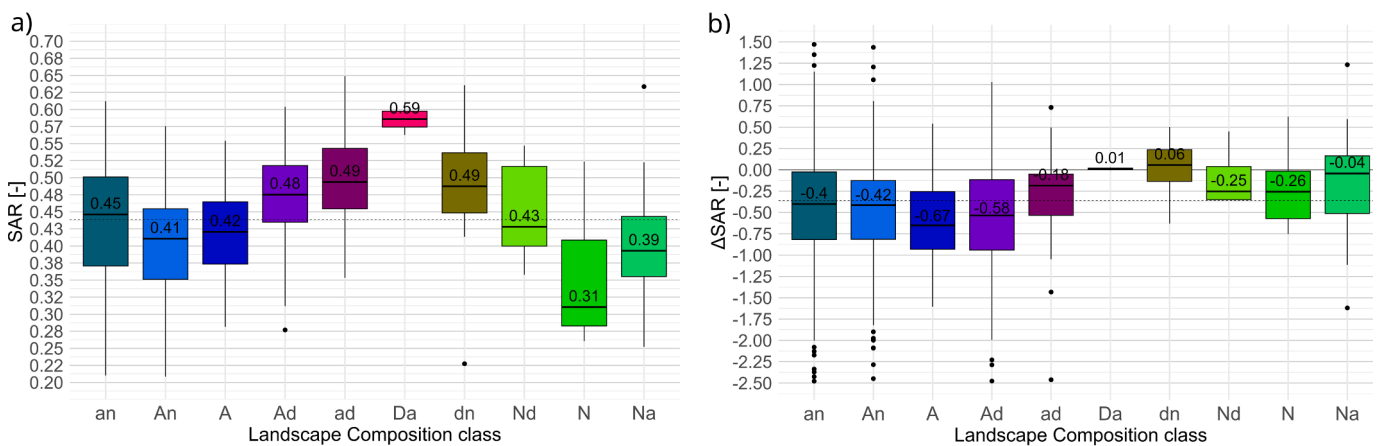


Fig. 5. a) SAR by Landscape Composition classes in 2012 and b) Δ SAR by Landscape Composition classes between 2012 and 2018. The colour coding follows the consolidated legend of the Landscape Mosaic classes which reflects the proportion of blue-Agriculture, green-Natural, and red-Artificial.

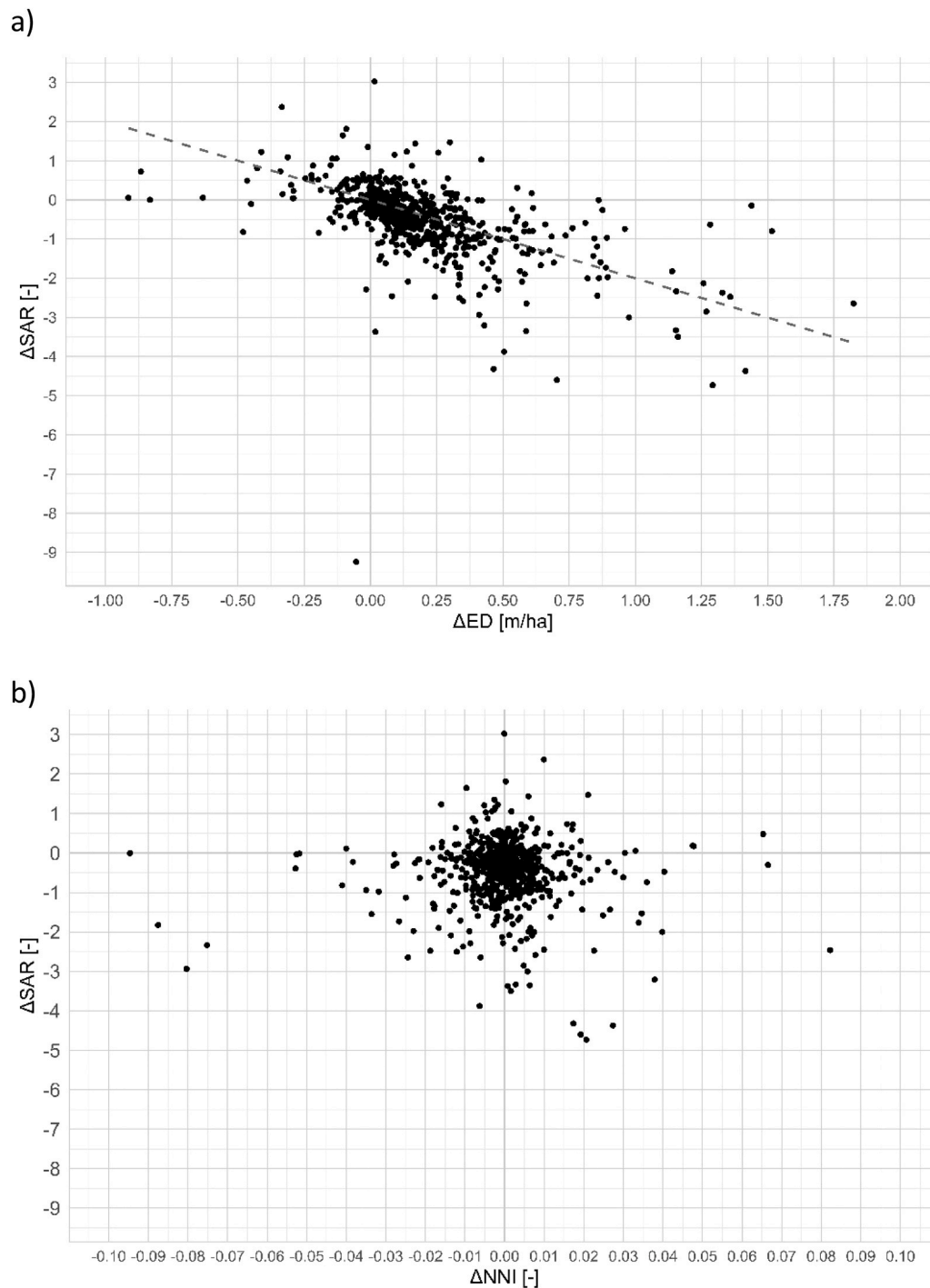


Fig. 6. Δ SAR (y-axis) in relation to changes in landscape metrics between 2012 and 2018: a) Edge Density (Δ ED) and b) Nearest Neighbor Index (Δ NNI).

was observed, particularly within areas that did not undergo land-use change. This increase in sealing derives from internal soil sealing within already artificial areas, rather than from new land-use conversion.

Conversely, a negative Δ SAR indicates that the SAR in 2018 was lower than in 2012; that is, a decrease in the ratio of sealed to artificial areas over time. This may result from the development of new artificial areas that contain a lower proportion of sealed surfaces compared to pre-existing ones. A negative value may also arise from the implementation of de-sealing measures that reduce existing sealed surfaces, either within existing artificial areas or in non-artificial areas, while the share of sealed areas in the new artificial areas that are established is the same of

the existing ones. However, recent studies indicate that de-sealing is still a minimal process (Vieillard et al., 2024), as also reflected in our estimation of the Net Soil Sealing indicator. Therefore, it can be concluded that negative values of Δ SAR generally point towards a trend of lower-intensity urban development at the urban scale.

Compared to other indicators such as Net Land Take (NLT) and Net Soil Sealing (NSS), which measure changes in absolute terms, Δ SAR describes relative changes with respect to the benchmark defined by the value of SAR in a specific year. The comparison with the ratio between Net Soil Sealing and Net Land Take in the analysed period shows that for NSS/NLT values above 0.75, Δ SAR is consistently positive. In those cases, each hectare of new artificial area corresponds to 0.75 or more

hectares of new sealed area. This happened in a few urban areas, around 1 in 6, where land take was relatively small or even negative between 2012 and 2018, while soil sealing continued at a relatively high rate. For NSS/NLT values below 0.25, Δ SAR is always negative. In those cases, more than half of the analysed FUAs, land take proceeded in combination with very low rates of soil sealing, determining a reduction in SAR. The added value of our indicator lies in its ability to capture the dynamics within the intermediate NSS/NLT range (0.25–0.75), where changes in SAR can be either positive or negative. For those urban areas, Δ SAR offers a clear indication of the direction of change, providing a more nuanced understanding of urban development trends and of their alignment with sustainability targets. In addition, we also computed NLT and NSS, which help to disentangle the contribution of compensatory processes (i.e. renaturalisation and de-sealing) within the analysed period and areas, thereby providing a more comprehensive context for interpreting SAR dynamics.

4.2. Temporal and spatial patterns of land take and soil sealing

Our findings indicate that in 2012 the median ratio of sealed to artificial areas within FUAs was 0.44. This value is close to the 0.52 reported by Decoville and Feltgen (2023) for 2018. The discrepancy can be explained by the fact that Decoville and Feltgen (2023) focused exclusively on the morphological city centers, i.e. the most densely built-up areas of 100 large cities, while our analysis considers the entire FUA. Such interpretation is supported by Kudas et al. (2024), who compared the share of artificial area and sealed area in eight Polish FUAs, revealing marked differences between core cities and related commuting zones. The same study reports a mean ratio of 0.27 between sealed and artificial areas for the analysed FUAs (Kudas et al., 2024), while our estimate for the same FUAs is approximately 0.40. This divergence reflects differences in the input data. Specifically, in our analysis we assessed the sealed area across the entire FUA, while Kudas et al. (2024) calculated the sealed area only within artificial surfaces. Additionally, another difference lies in the use of the imperviousness density map corrected in 2024 (EEA et al., 2024) in our analysis, whereas Kudas et al. (2024) rely on the pre-correction version.

Overall, from 2012 to 2018, we observed a decrease in SAR values (median of -0.36), indicating a shift towards lower-intensity urban development in most urban areas. Over the same period, Tóth et al. (2022) assessed the increase of sealed area, aggregated by land-use classes and MAES ecosystem types, for the entire sample of EU and UK FUAs, which corresponds to the same sample used in our analysis. Our findings indicate an increase of approximately 1.2% in sealed areas compared to the initial sealed areas within the sample. In comparison, Tóth et al. (2022) estimated the increase in sealed area within FUAs between 2012 and 2018 to be around 2.6%. The discrepancies between our findings and theirs can be attributed to the different input data, since Tóth et al. (2022) quantified soil sealing by assigning an average percentage of sealed area to each Urban Atlas class based on the product specification and on expert knowledge. Considering that we found a general reduction in SAR during the analysed period, maintaining constant values could have contributed to an overestimation of the sealed area in 2018. The comparison highlights the importance of updated and comparable datasets to consistently track soil sealing processes across Europe.

Both SAR and Δ SAR show clear differences across regions and countries, in line with previous studies. For example, previous research by Colsaet et al. (2018) highlights the influence of geographical location on land take. Consistent with this, our results indicate that, in 2012, urban areas in Northern Europe have lower SAR values compared to those in Central and Southern Europe. This pattern can be linked to several factors, notably the lower population densities in Northern Europe (Kasanko et al., 2006) and long-standing planning principles aimed at safeguarding green space provision (Khoshkar et al., 2018). In the UK and Ireland, the lowest Δ SAR values suggest that green spaces

are relatively well preserved even in densely populated areas. This region benefits from a higher-than-average share of natural and semi-natural areas, although notable national differences remain, with the UK showing a more compact urban form than Ireland (Hauru et al., 2015). In Southern Europe, near-zero Δ SAR values indicate a stable ratio between sealed and artificial areas, largely due to compact urban structures and the limited availability of green spaces (Kasanko et al., 2006). This scarcity is often linked to ongoing construction pressure and increasing land privatisation (Kabisch et al., 2016). Across Europe, the potential to increase SAR (positive Δ SAR) is highly uneven and often intersects with existing climate, social, and environmental vulnerabilities. Southern Europe, for example, is recognised as one of the region's climate-change hotspots (Lazoglou et al., 2024).

4.3. The influence of landscape composition and urban form

Our first hypothesis focused on the influence of landscape composition on Δ SAR. Specifically, we expected a greater decrease in SAR in FUAs with predominant agricultural land cover. Consistent with this hypothesis, several studies have shown that land take within FUAs occurs mainly at the expense of agricultural land (Barbosa et al., 2017; De Cos et al., 2025; Gardi et al., 2015), and that the main driver of land take in Europe is the expansion of low-density residential suburbs (Colsaet et al., 2018; Orsi, 2023). Overall, despite a limited statistical reliability due to the small number of FUAs in each landscape composition class, our results confirm the hypothesis. In fact, urban areas with more than 60% agricultural land show the most negative Δ SAR values, indicating a trend towards lower-intensity urban development. This could be explained by the presence of extensive agricultural areas available for conversion and the limited area of existing artificial surfaces that could be further sealed through densification actions. On the contrary, Δ SAR is closer to zero in FUAs where artificial land makes up more than 40%, and the value of the indicator increases as the share of agricultural land becomes smaller. This suggests that, in FUAs where urban cores occupy a large proportion of the area, urban growth tends to favour the densification of existing settlements or their expansion through medium-density developments. It can also be noted that FUAs with a prevalence of natural land cover consistently show higher-than-average values of Δ SAR, which could be explained by the higher costs associated with the conversion of forests compared to agricultural land, but also by the efficacy of protection regimes aimed at safeguarding natural areas.

Our second hypothesis examined whether the spatial characteristics of urban form influence changes in SAR. We tested this by analysing the relationship between Δ SAR and changes in three landscape metrics over the study period: Edge Density (ED), Percentage of Landscape Adjacency (PLADJ), and the Nearest Neighbour Index (NNI). The indicators used to define urban form are selected based on the spatial scale of the analysis (i.e., the FUA). This choice led to the exclusion of several indicators, such as building density. The retained indicators were selected based on their availability, simplicity, and relevance, with each capturing a different dimension of urban form. However, these indicators were primarily used to characterize the shape and configuration of artificial surface patches, rather than fully capturing the overall complexity of urban form. As a result, the observed relationship between Δ SAR and urban form mainly reflects specific aspects of urban structure rather than its full complexity. Specifically, ED reflects the complexity and fragmentation of artificial area boundaries, PLADJ quantifies the degree of clustering of artificial land patches, and NNI evaluates the spatial distribution of these patches through inter-patch distances. Our results indicate that FUAs characterised by increasing compactness and aggregation, reflected in lower ED and higher PLADJ values, exhibit higher values of Δ SAR. All cities with a negative change in ED and a positive change in PLADJ show a positive or slightly negative Δ SAR, indicating a shift toward more intensive urban development. This confirms the hypothesis that the ratio between sealed area and artificial area increases when the urban form becomes more compact, e.g. through infill

development or through edge expansion, when it tends to simplify complex geometries and define clear urban boundaries. On the contrary, when simple compact shapes become more complex through the addition of new artificial areas contiguous or fully separated from the existing ones, the ratio between sealed area and artificial area tends to decrease, suggesting that these types of interventions are usually characterised also by a lower density or intensity. Nevertheless, only about 8% of the FUAs in our sample display this combined trend of compactness and aggregation of artificial land patches. In contrast, the majority of FUAs demonstrate a tendency toward more complex forms and greater spatial dispersion of artificial land.

The third landscape metric, NNI, did not show any significant correlation with Δ SAR, indicating that this dimension of urban sprawl does not appear to be linked to changes in SAR. NNI quantifies the spatial clustering of artificial patches by comparing the average observed distance of the patches from their nearest neighbors to the expected average distance in a random distribution. The NNI has been used to describe a dimension of sprawl, i.e. the dispersion of the patches as opposed to their clustering. Its lack of correlation with Δ SAR and with the changes in the other landscape metrics computed for the sample may suggest that the dispersion of artificial areas is not linked to the share of sealed areas within them. That is to say, the characteristics of the new artificial areas built during the analysed period are not dependent on their spatial relationship to the existing ones. However, it should be noted that the interpretation is not straightforward, as some changes, e.g. the expansion of existing patches, might not be captured by the metric while others, e.g. the creation of new patches close to existing ones, might affect both the observed and the expected average distance in hardly predictable ways.

4.4. Inform land take and soil sealing reduction strategies

While SAR and Δ SAR are not directly linked to existing policy targets, they can support municipal baseline assessments by helping identify strategies and actions aimed at achieving these targets. They can also be used to evaluate the consequences of past planning decisions and to identify potential unforeseen or undesirable effects of implemented strategies. As relatively easy-to-compute indicators, SAR and Δ SAR provide a useful link between planning practice and European policy objectives, although their interpretation requires consideration of the local context.

For example, urban densification has been widely promoted as a fundamental strategy to reduce land take by making a more efficient use of existing artificial land (Chihambakwe and Moyo, 2024). However, previous studies have already highlighted how urban densification processes, while contributing to more compact forms, often result in increased soil sealing that reduce the extent and size of green spaces (Balıkcı et al., 2022). The latter are crucial to provide various benefits to urban residents, including cultural and aesthetic values, such as beauty, inspiration, and a sense of belonging, but also regulating ecosystem services that are essential for the health and livability of urban areas in the face of climate change (O'Riordan et al., 2021). Several authors have discussed such trade off, calling for “green densification processes” (Erlwein and Pauleit, 2021) that minimise their impact on urban green spaces, for example by prioritising vertical urban growth (Romano et al., 2023), or by compensating densification with de-sealing (Calzolari et al., 2020; Conticelli et al., 2024).

By relating land take and soil sealing, our indicator provides a clearer understanding of how the balance between these two processes evolves, helping avoid situations where the “no net land take” is achieved through too extensive soil sealing or where low sealing is accompanied by an unsustainable expansion of artificial areas.

In the previous example, indicators related to Net Soil Sealing and Net Land Take alone would be insufficient to assess the interactions between the two trends and their effects on the specific local context. They capture how soil sealing and land take have evolved over the time

frame, but they do not offer a way to compare that evolution with the city's baseline condition or with other cities and urban areas. On the contrary, SAR values can be compared across cities with similar geographic, historical, and morphological conditions to determine a locally acceptable densification target. For example, in urban areas where the value of SAR is already quite high, it could be appropriate to aim at maintaining it or reducing it through targeted de-sealing strategies, e.g. involving large vacant areas. On the contrary, in urban areas characterised by a low value of the indicator, policies could aim at its increase by promoting densification and infill development. Then, Δ SAR would inform planners and decision-makers of the change relative to the baseline condition, thus providing a synthetic description of the effects of land take, soil sealing, renaturalisation, and de-sealing processes.

Therefore, adopting the proposed indicators at the regional (LAU) and local levels (core cities or specific local administrative units), alongside indicators such as Net Land Take and Net Soil Sealing directly linked to the targets, can guide urban planning strategies towards sustainable development pathways that allows achieving both “no net land take” and “no net soil sealing” with minimal negative impacts. It is important to underline that the two indicators do not require Net Land Take or Net Soil Sealing for interpretation; rather, they act as complementary indicators that support progress toward both “no net land take” and “no net soil sealing” targets. Their innovative contribution lies precisely in ensuring that neither process is neglected, offering an integrated perspective that captures both dynamics simultaneously.

In countries like France, Germany, Austria, Luxembourg, and Belgium, where quantitative limits to land take (but not to soil sealing) have been set (EPSON et al., 2024), the Δ SAR indicator can be valuable for tracking policy implementation and for defining more realistic intermediate targets. Another important aspect is the broader spatial planning policy context. General planning strategies, particularly densification policies, may contribute significantly to achieving the European “no net land take” target even when they are not explicitly linked to it. For example, in countries such as Germany, France, and England, where densification strategies have been promoted (Dembski et al., 2025), the Δ SAR indicator may serve as a useful indicator for assessing the effectiveness of these policies, while ensuring that the importance of urban green spaces is not overlooked.

4.5. Limitations of the study and future directions

One constraint that affected the results is related to the spatial resolution of the input data. In this study, we relied on imperviousness data aggregated at a 1 km spatial resolution, derived from higher-resolution datasets (10 m and 20 m). The Imperviousness Density Map is available only until 2018. Although this relatively coarse resolution may affect the precision of the results and reduce processing time, it does not alter the main objective of the SAR analysis, which is to capture temporal variations in SAR values (Δ SAR). Higher-resolution datasets, such as the 10 m CLCplus Backbone, are available; however, these datasets only became accessible from 2018 onwards. Consequently, future research could test the SAR using CLCplus Backbone data for sealed area assessment over different time periods.

Future studies could consider extending the temporal scope beyond six years to better capture long-term urban transformation processes and to monitor the progress towards EU targets. In addition, applying the analysis to different time periods (for example, in Germany after the introduction of national land take target in 2017) could help assess whether countries adopting national targets on land take are progressing more rapidly towards these European targets compared to countries without them. A longer timeframe would also allow for more robust comparisons of urban development trends across European urban areas. In this respect, while this study employed Functional Urban Areas (FUAs) as the spatial reference units, future studies could explore alternative spatial units, especially those linked to local administrative units. This would enable more localised analyses and provide finer-scale

insights for urban planning, for example by assessing Δ SAR separately within the urban core and the commuter belt of each FUA. In addition, future studies could further investigate specific contexts with especially high or low values of the indicators to analyse the underlying causes, possibly revealing the role of local plans and policies.

Testing the study's hypotheses using alternative classifications of landscape composition (for Hypothesis 1) and different metrics and indicators (for Hypothesis 2) could strengthen the robustness of the findings. While a range of complex metrics exist for assessing urban form, this study adopted relatively easy-to-compute and replicable indicators, providing an accessible starting point for broader analyses. Testing additional or alternative indicators could help better clarify the relationship between Δ SAR and urban form by capturing its complexity more effectively, particularly with regard to the spatial distribution of artificial patches.

Finally, not all observed spatial patterns are supported by statistical analyses, due to the limited number of urban areas per country and region, which reduces the statistical representativeness. Nevertheless, these descriptive observations remain valuable, offering novel insights into the spatial dynamics of the ratio between soil sealing and land take, an area that is still relatively underexplored in the literature.

5. Conclusion

Our study introduces a new indicator, the Sealed-to-Artificial area Ratio (SAR), and its temporal variation (Δ SAR), developed to explore the relationship between land take and soil sealing processes in urban areas. Across the 27 EU countries and the United Kingdom, a general decrease in SAR was observed between 2012 and 2018, indicating a shift toward lower-intensity urban development in many urban areas. Regional variations emerge, with the UK and Ireland showing a greater decrease, while Southern Europe exhibited a smaller reduction.

Two hypotheses were tested and confirmed, showing that landscape composition and urban form influence the Ratio. SAR tends to decline as urban areas become less compact and more dispersed, particularly in areas dominated by agricultural land rather than artificial surfaces. In such contexts, planning strategies such as densification, de-sealing, and the intensification of existing artificial areas may help increase the SAR, promoting higher-intensity urban development.

Although SAR and Δ SAR are not directly linked to existing policy targets, they provide valuable insights into the potential unintended effects of strategies aimed at achieving exclusively “no net land take” or “no net soil sealing.” SAR values can be used to assess whether the combined effects of land take and soil sealing are moving in the desired direction. Moreover, the spatial variability captured by SAR and Δ SAR highlights their potential to inform planning and policy interventions, supporting the achievement of European sustainability targets. By bridging the gap between land take and soil sealing in the literature through a single synthetic indicator, SAR and its temporal variation offer a novel perspective on urban development, enabling a more nuanced understanding of how cities grow and transform in pursuit of “no net land take” and “no net soil sealing” targets. By complementing existing indicators, this innovative metric could support the monitoring and assessment of spatial planning processes towards more sustainable urban development.

CRedit authorship contribution statement

Silvia Frezzi: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Cortinovis:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Davide Geneletti:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.landusepol.2026.108321](https://doi.org/10.1016/j.landusepol.2026.108321).

Data availability

The data are available in the Supplementary Material.

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