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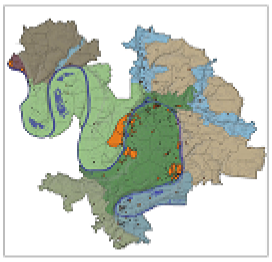
> Sadaf Pirouzi
> Fabiana Fabri
> Loïc Sauvée

# Prioritizing brownfields transformation towards green infrastructure

## The case of Rouen metropolis



> #Numéro 7
> Territoires soutenables en devenir
> Working papers
> INTERACT - Innovation, Territoire, Agriculture & Agroindustrie, Connaissance et technologie (UniLaSalle)
> Agriculture et technologie - > Cités intelligentes - > Développement durable

## To cite this article

Sadaf Pirouzi., Fabiana Fabri., Loïc Sauvée. "Prioritizing brownfields transformation towards green infrastructure. The case of Rouen metropolis", 10 May 2024, *Cahiers Costech*, numéro 7.
URL https://costech.utc.fr/CahiersCostech/article189.html

## Résumé

Avec l'augmentation de la population mondiale, les villes s'étendent, ce qui entraîne des problèmes environnementaux importants et une demande croissante d'amélioration des conditions de vie des habitants. En réponse à ces préoccupations, la réutilisation des terrains aménagés offre une solution potentielle. Dans la métropole rouennaise, plus de 400 friches industrielles ont été identifiées et font l'objet de mesures de régénération. Au-delà de l'attribution aléatoire, cette étude vise à fournir aux décideurs et aux chercheurs un outil pratique pour hiérarchiser les friches industrielles à transformer en infrastructures vertes urbaines. À l'aide d'une méthode d'évaluation multicritères basée sur un SIG, l'adéquation des sites et les exigences écologiques urbaines ont été prises en compte, et le degré de coordination entre les deux a été calculé. Cette approche est conforme aux principes du développement durable, car elle permet de relever une série de défis environnementaux et d'offrir des avantages considérables à la société et à la région locale. La technique d'analyse basée sur le SIG présentée peut être utilisée dans le cadre d'un processus d'aménagement du territoire applicable à n'importe quelle ville. Elle permet d'identifier les zones propices à l'expansion de l'infrastructure verte.



## Abstract

As the global population increases, cities spatially expand, leading to notable environmental challenges and growing demand for improved living conditions for residents. In response to these concerns, reuse of developed lands offers a potential solution. In Rouen metropolis, more than 400 brownfields were identified, which is subject to regenerate brownfield measures. Moving beyond random allocation, this study aimed to provide decision-makers and researchers with a practical tool for prioritizing brownfields to transform into urban green infrastructure. Using a GIS-based multi-criteria evaluation method, sites' suitability and urban ecological demands were considered, and the coupling coordination degree between them was calculated. This approach is in line with the principles of sustainable development, by addressing a range of environmental challenges and delivering considerable benefits to society and the local area. The presented GIS-based analysis technique can be used as part of a spatial planning process, applicable to any city. It provides support to identify suitable areas for green infrastructure expansion.


## Author(s)


Sadaf Pirouzi works as a researcher within the InTerACT research unit at Institut Polytechnique UniLaSalle, Rouen. In 2024, she attained her second master's degree in Urban Agriculture and Green Cities from Institut Polytechnique UniLaSalle. Prior to this, she completed her first master's degree in Regional Planning at Tehran University, Iran, in 2019, and her bachelor's degree in Urban Engineering from the University of Art, Tehran, Iran, in 2016. Currently, her research primarily focuses on Bringing nature back to the cities, with a specific emphasis on the redevelopment of brownfields and the planning of multifunctional green infrastructure.

Fabiana Fabri holds a PhD in Geography and Environmental Analysis from the Federal University of Minas Gerais (UFMG) in Brazil. She currently works as a Research Professor and head of UsinoVerT Chair *Factories & Territories* at Institut Polytechnique UniLaSalle, Rouen, since 2021. She is also a member of the InTerACT research unit at Institut Polytechnique UniLaSalle, Rouen and her research focuses on cartography and GIS applied to the analysis of the sustainable development of the territory. Research profile at CV HAL

Loïc Sauvée is director of the InTerACT research unit at institut polytechnique UniLaSalle (Beauvais and Rouen) and associate researcher at COSTECH laboratory, the Université de Technologie de Compiègne, France. He earned a Habilitation to supervise research (HDR) in management sciences from the University of Montpellier in 2002 and a post doctorate from Purdue university, USA, in 1995. He is chairman of IFAMA Europe (2021-2024) and member of the board of directors of IFAMA. His current research aims to deepen the understanding of governance in organizations, networks and territories in the perspective of sustainable transitions and transformations. Research profile at CV HAL

## Outline



# 1. Introduction

According to the ‘World Urbanization Prospects’ by the (Nations, U., 2014), urbanization has accelerated significantly in recent decades, with growth rates projected to triple by the middle of the century, reaching an estimated 2.4 per cent (Artmann et al., 2019). This growth is taking place at a time when urban economic dynamics are changing, with industrial sites that were once central to urban productivity now being abandoned (Hou et al., 2023). While, demolition and abandonment have historically been common strategies for addressing post-industrial landscapes (Rea & Corinne, 1991), to follow the no take land policies , this lands need to be redeveloped and given new life,

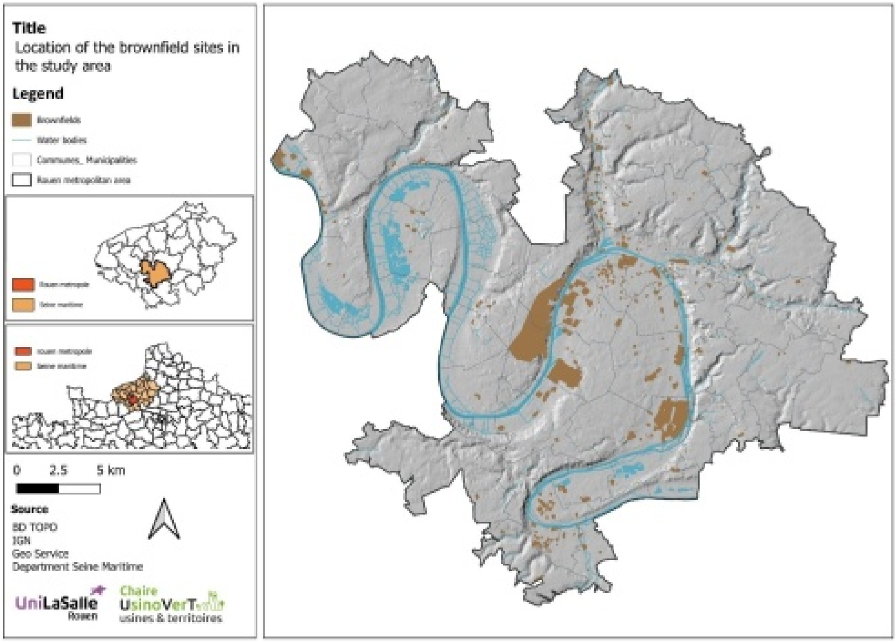
achieving a more sustainable urban setting (Loures, 2015).
Brownfield redevelopment can contribute to the creation of urban green spaces, generating a wide range of ecosystem services that go beyond the current conditions, thus promoting environmental quality (Masiero et al., 2022). To apply the greening brownfield strategy, new green spaces should be part of an urban green infrastructure, which means providing and improving the infrastructural functions, such as mobility, stormwater system, ecological networking and social issues (Sanches & Mesquita Pellegrino, 2016).
Determining the priority of land use stands out as one of the most intricate challenges in urban planning (Kazemi & Hosseinpour, 2022). Land/ Site suitability analysis is a systematic process used to assess the suitability of a particular area for a proposed use, revealing the compatibility of a site with its intrinsic characteristics and classifying it as either suitable or unsuitable (Malczewski, 2004). Due to the large number of attributes considered during the site suitability analysis, the process is often identified as Multi-Criteria Evaluation (Mugiyo et al., 2021).
Although brownfields have the potential to offer some ecosystem services, their current functionality is limited (Chowdhury et al., 2023). Therefore, green infrastructure as “a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (European Commission, 2013)” is a way of transforming brownfields into multifunctional green spaces. The potential benefits of urban green infrastructures could include enhancing of urban biodiversity, climatic regularization, atmospheric purification, storm water management and flood alleviation, and the contribution to energy savings. They also perform range of social and cultural benefits (Madureira & Andresen, 2014). The multiple functions of green infrastructure assets are of particular importance for land use policy and spatial planning (Ustaoglu & Aydinoglu, 2019).
Numerous studies have investigated the potential suitable brownfields for regeneration as green infrastructure, utilizing two common GIS-based multi-criteria methodologies: site suitability analysis and multifunctional green infrastructure planning. However, there is a recognized need for the integration of these approaches. (Feng et al., 2023) proposed a methodological integration by Coupling Coordination Degree Methodology and employing quadrant division, thereby combining these two previously independent methods.
The method was applied to Rouen metropolis, France. The following research aims were proposed: 1) to present a comprehensive model supporting public authorities and researchers in the transformation of brownfields into multi-functional urban green infrastructure. 2) to consider the conditions of the site together with the ecological requirements of the area in the decision-making process 3) to raise

awareness among stakeholders to the potential of the brownfields to be regenerated as a green space. 4) to create and use of spatial analysis, with the help of maps and satellite images, in order to have a better understanding of the territory.
The article continues with the ’Study Area’ section, which provides an overview of the Rouen metropolis and how the brownfields are connected to different aspects of the territory. The ’Methodology’ section then outlines the proposed approach, which integrates the analysis of site suitability and urban ecological demands through the novel methodology of coupling coordination degrees. This is followed by the ’Results’ section, which presents the empirical findings of the study. In the ’Discussion’ section, these results are analyzed and interpreted. Finally, the ’Conclusion’ section summarizes the main findings of the study and offers implications for future research.

## 2. Study Area

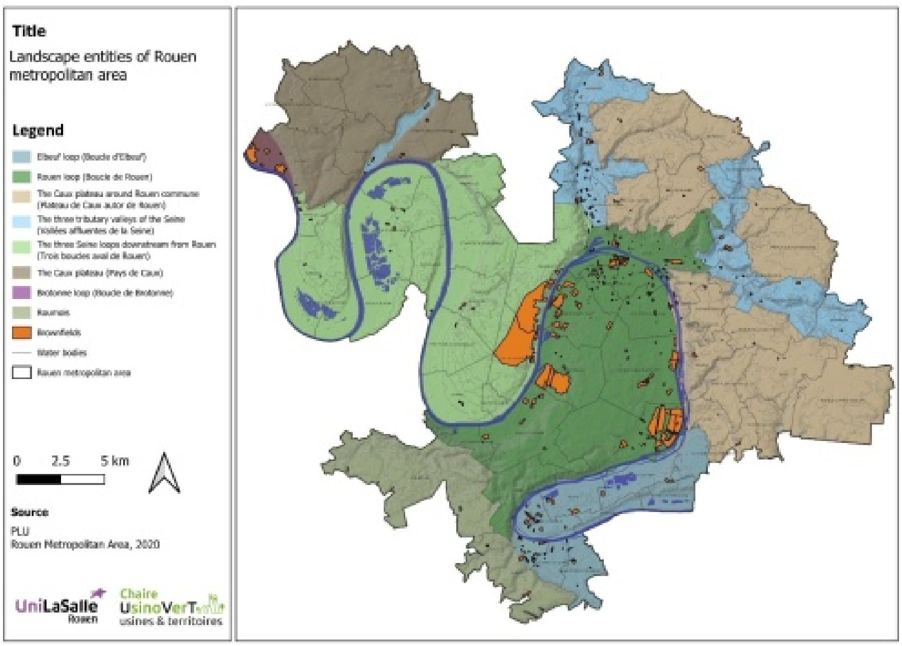
The Normandie region faces a numerous of varied brownfields. Recently, France, along with other European countries, has introduced green deal proposals that outline programmatic measures to achieve territorial sustainability by transforming brownfields into Sustainable Industrial Areas (Sessa et al., 2022). Rouen Metropolis is one of these targeted territories. Influenced by the $19^{th}$-century industrial expansion of textile production, which took advantage of the hydraulic power provided by the rivers, the area experienced the emergence of brownfields after the closure of textile factories in the 1960s (Rouen metropolis, 2020). Thus, prioritizing brownfields for green infrastructure is crucial to optimize the layout of urban green space in this territory.
The study is conducted in the Rouen metropolis, Normandie region, France, which covers approximately 663.8 $km^2$ (Figure 1) and includes 71 municipalities. Located in the south of the Seine-Maritime department, the area had a total population of 496,629 inhabitants at the end of 2020. The distribution of brownfields within the metropolis aligns with the location of the rivers and valleys, with a few brownfields existing in the plateaus. Specifically, the municipalities situated on the left bank of the Seine, such as Oissel, Rouen (left bank), and Petite and Grand Quevilly, contain a large number of brownfields, while several brownfields are also present in the municipalities surrounding the Cailly river. In the latest Cartofriches dataset, within the Rouen metropolis, a total of 416 sites have been identified as brownfields.

Figure 1: Map of the brownfields’ location (Source: Done by the author)



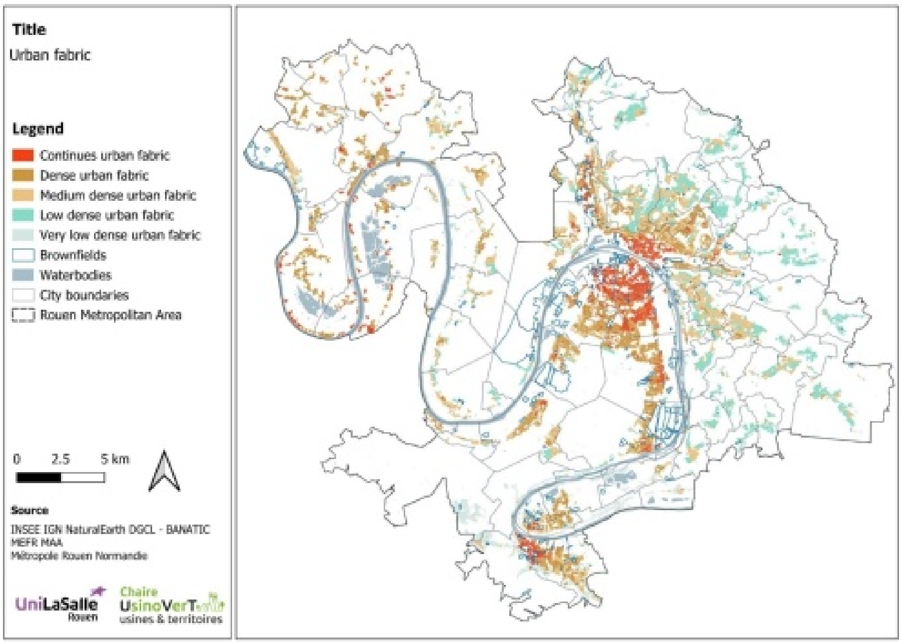

The Rouen metropolis exhibits diverse landscape features, as identified by (La DREAL Normandie, 2011). Areas surrounding the Seine valley are characterized by alluvial plains, lush green hills, and steep terrain. Urban and industrial elements dominate the Rouen and Elbeuf loop, while downstream areas of Rouen loop transition to more verdant landscapes with expansive fields and orchards. The limestone plateau showcases large-scale farming and polyculture systems, and tributary valleys boast wooded hillsides and relatively steep slopes. According to Figure 2, brownfields are primarily concentrated in the Rouen loop (especially on the left bank), the Elbeuf loop, and the three tributary valleys of the Seine.

Figure 2: Map of the landscape entities (Source: Done by the author derived from ((Rouen metropolis, 2020))



The territory has a rich and varied natural heritage, including forests, wetlands, rivers, limestone hills, alluvial terraces and agricultural land (COP 21 & Métropole Rouen Normandie, 2023). The annual rate of consumption of natural, agricultural and forest areas between 2012 and 2018 showed a significant decrease compared to the previous period from 1999 to 2012, from 98 hectares to 75 hectares per year ((Réunion du conseil Métropole Rouen Normandie, 2021). This decrease aligns well with the reduction objectives established by the (Métropole Rouen Normandie, 2015), demonstrating a concerted effort to control land consumption and preserve natural resources.
Rouen city and its adjacent areas have the highest population density in the metropolis, with more than 2500 inhabitants per square kilometer. City is characterized by a long period of absolute and then relative decentralization. The outer ring of Rouen remains the fastest-growing zone of the city, indicating that growth is predominantly concentrated in the suburban areas rather than the city center (Dembski et al., 2021). The Rouen, Sotteville-lès-Rouen and Le Petit-Quevilly cities have the densest built-up area (Figure 3), with an average land sealing degree of more than 80 percent. The majority of brownfields are located on the left bank of the Seine, adjacent to continues and dense sealed area. More specifically, brownfields in Rouen, Petite Quevilly and Elbeuf municipalities are located in close proximity to the continuous built-up area.

Figure 3: Map of the urban built-up area (Source: Done by the author)




## 3. Methodology

This section provides an overview of the methodological approach, which includes several key stages. First, the collection and processing of relevant data is outlined, followed by a spatial priority assessment that integrates site suitability analysis and multifunctional green infrastructure planning techniques. This is followed by a detailed evaluation of a coupling coordination model that aims to integrate these two methodologies. Furthermore, the matching relationship between site suitability and urban ecological demands is explored to inform the prioritization of brownfield sites.

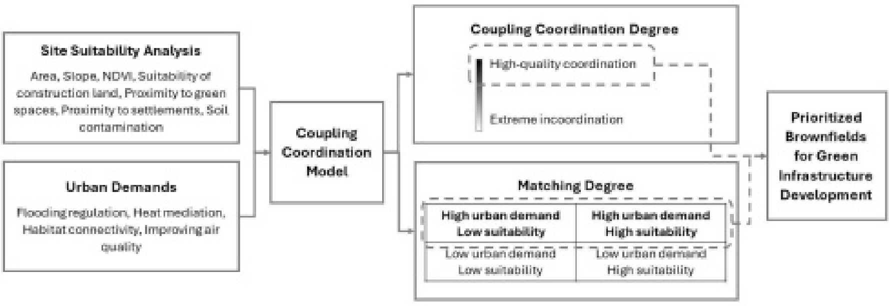
## 3.1. Methodological Framework

Multiple studies have documented the contribution of spatial indicators to examine either site suitability or planning methods for green infrastructure multifunctionality through quantitative and spatial approaches. The new perspective, derived from (Feng et al., 2023), lies in quantitatively measuring both site suitability and urban multifunctionality simultaneously. To achieve this objective, three steps need to be taken, as shown in the framework (Figure 4):

1. Site suitability analysis of each brownfield assessed with seven criteria including area, slope, NDVI, suitability of construction land, proximity to green spaces, proximity to settlements, and soil contamination.
2. Considering urban ecological demands that could be addressed through green infrastructure planning including flooding regulation, heat mediation, habitat connectivity, and improving air quality.
3. The coupling coordination model is used to determine the levels of coordination between site suitability and, urban demands followed by an analysis of their matching degree through quadrant division.

As a result, the brownfields with high coupling coordination and high matching degree are prioritized for planning a multifunctional green infrastructure.

Figure 4: Methodological framework ((Source: proposed by the author derived from ((Feng et al., 2023))




## 3.2. Data and Processing

The selection of appropriate datasets is fundamental, considering reliability of findings. In this section, a comprehensive overview of the datasets employed in the study is presented. In Table 1, it is clearly documented where each dataset comes from and how it has been used.

Table 1: Datasets and application of data in the analysis

| Data | Application | References |
|---|---|---|
| Brownfields shapefile | Assessment of site suitability and urban demands | Cartofriches, CEREMA https://cartofriches.cerema.fr/cartofriches/ |
| Multi-layer shapefile | Assessment of site suitability and urban demands | Départementale Shapefile Seine-Maritime, 2021 https://geoservices.ign.fr/ressource/158243 |
| DEM[7] | Assessment of slope | U.S. Geological Survey (USGS) https://earthexplorer.usgs.gov/ |
| Land use 2018 shapefile | Assessment of local temperature regulation | Urban Atlas Land Cover/Land Use 2018 https://doi.org/10.2909/fb4dffa1-6ceb-4cc0-8372-1ed354c285e6 |
| RSI[8] Landsat 8 | Assessment of local temperature regulation, NDVI, and proximity to settlement | U.S. Geological Survey (USGS) https://earthexplorer.usgs.gov/ |
| Tree Cover Density 2018 | Assessment of local temperature regulation | Tree Cover Density 2018 (Raster 10 m) https://land.copernicus.eu/en/products/high-resolution-layer-tree-cover-density/tree-cover-density-2018 |
| Street view on Google earth | Assessment of suitability of construction land | Google Earth https://earth.google.com/web/ |
| Flooding risk shapefile | Assessment of flooding reduction | Territoire à risque d'inondation (TRI), 2020 https://www.geocatalogue.fr/Detail.do?fileIdentifier=64dc3015-8cb0-4c42-aa7a-9ccd8e34aeb5 |
| Air quality 2019 (PM10) | Assessment of air purification | European air quality (2019) https://www.eea.europa.eu/en/datahub/datahubitem-view/b51e1091-4459-4a1e-8dbc-dd7a30949b90 |

## 3.3. Spatial Priority Assessment

### 3.3.1. Site suitability analysis

In this study, an index system (Table 2) was developed to analyse the suitability of brownfields for regeneration as green infrastructure sites by synthesizing literature review, and insights derived from the study area. Seven site attribute index factors were selected, including Area, Slope, NDVI, Suitability of construction land, Proximity to green area, Proximity to settlement area, and Soil contamination. In addition to identifying appropriate criteria, the characteristics of each index were considered by reference to the relevant literature and a rating was assigned.

Table 2: Index grading criteria for site suitability assessment

| Criteria | Index | Value | Explanation |
|---|---|---|---|
| Suitability of construction land | green/ without building | 5 | According to the latest Google Street View data, this index suggests that the more degraded and vacant the site, the more suitable it is to be regenerated as green infrastructure. |
| | sealed/ without building | 4 | |
| | partially green/ with building | 3 | |
| | only building | 2 | |
| | woodland/ with temporary land use | 1 | |
| Area | 10 ha ≤ area | 5 | The index indicates that the larger the area, the greater the biodiversity (Spotswood et al., 2019), and the greater the benefits related to reducing local temperature, collecting rainwater, providing recreational space, etc (Feng et al., 2023) |
| | 5 ha ≤ area < 10 ha | 4 | |
| | 2 ha ≤ area < 5 ha | 3 | |
| | 1 ha ≤ area < 2 ha | 2 | |
| | area < 1 ha | 1 | |
| NDVI | 0.44 < NDVI | 5 | A higher NDVI value indicates greater diversity and stability within the vegetation community. As such, NDVI provides an insight into the status of native vegetation, and their potential to provide habitat and support biodiversity (Feng et al., 2023). |
| | 0.33 ≤ NDVI < 0.44 | 4 | |
| | 0.20 ≤ NDVI < 0.33 | 3 | |
| | 0.14 ≤ NDVI < 0.20 | 2 | |
| | NDVI < 0.14 | 1 | |
| Slope | Slope ≤ 5% | 5 | The slope analysis is essential to detect potential sites for green land development watershed management, afforestation, etc (Ustaoglu & Aydinoglu, 2019). The low-slope areas are highly suitable for the development of urban green infrastructure (Gelan, 2021). |
| | 5 % ≤ Slope < 10 % | 4 | |
| | 10 % ≤ Slope < 15 % | 3 | |
| | 15 % ≤ Slope < 20 % | 2 | |
| | 20 % < Slope | 1 | |
| Proximity to green area | Proximity to very low dense green | 5 | The lower the proximity to green spaces, the higher the value of the site to be developed as green infrastructure due to the increased connectivity of the green network. |
| | Proximity to low dense green | 4 | |
| | Proximity to medium dense green | 3 | |
| | Proximity to high dense green | 2 | |
| | Proximity to very high dense green | 1 | |
| Proximity to settlement area | Proximity to continues urban fabric | 5 | Places with a higher number of people with crowded places near the high population density required access to the open green spaces. The areas that have high population density are highly suitable for developing green space (Dağıstanlı et al., 2018). |
| | Proximity to dense urban fabric | 4 | |
| | Proximity to medium dense urban fabric | 3 | |
| | Proximity to low dense urban fabric | 2 | |
| | Proximity to very low dense urban fabric | 1 | |
| Soil contamination | Contaminated BASIAS sites | 4 | Bioremediation is considered a safe economical, efficient and sustainable technology for restoring the contaminated sites (Megharaj & Naidu, 2017). |
| | Non-contaminated BASIAS sites | 1 | |

The next step involves weighting the criteria, a process commonly facilitated by Analytic Hierarchy Process (AHP) pairwise comparisons. The final result of the site suitability analysis is obtained by overlaying the weighted scores in QGIS. The calculation formula is:

$$S = \sum_{i=1}^{n} WiXi$$

S: Site suitability value
Xi: The value of each index

Wi: The weight of each index

### 3.3.2. Multifunctional green infrastructure planning

This section examines the environmental issues that could be addressed through the development of green infrastructure. For this study based on the study area and the available data, the four indicators for developing green infrastructure in brownfields have been selected, including flooding risk, high land surface temperature, habitat fragmentation and air pollution.

Table 3: Index criteria for multifunctional green infrastructure planning

| Criteria | Index | Explanation |
|---|---|---|
| Local temperature regulation | $Index_{(i)} = \left(Mean\ temperature\ land\ use_{(i)} \times (1 - Percent\ green\ cover_{(i)})\right) + (Mean\ temperature\ green\ cover_{(i)} \times Percent\ green\ cover_{(i)})$ | The mean land surface temperature was calculated for each land use and land cover units and green coverage of the units. The index establishes the influence of green cover on surface temperature for each land use unit. |
| Flooding reduction | Frequent, medium , and extreme flooding risk scenarios | The flood risk assessment for the Rouen metropolis has been derived from les territoires à risque important d'inondation (TRI) document, which was published in 2014. |
| Habitat connectivity improvement | Habitat fragmentation from low to high | The habitat fragmentation was calculated utilizing FragScape extension in QGIS. |
| Air purification | The amount of particulate matter (PM10) in the air | European air quality data (interpolated data and station points) 1 km grids |

After obtaining the urban ecological demands, the urban demand values of brownfield locations were calculated by the zonal statistical tool in QGIS, which were then divided into five levels using the natural breakpoint method, with 1–5 representing “very low”, “low”, “medium”, “high” and “very high”, respectively. Then, with AHP methodology, the weight of each index was calculated. The final result of the comprehensive urban demand is obtained by overlaying the weighted scores in QGIS. The calculation formula is:

$$D = \sum_{i=1}^{n} WiXi$$

D: Comprehensive demand value
Xi: The value of each index

Wi: The weight of each index

### 3.3.3. Assessment of coupling coordination model

Originating from physics, coupling refers to the mutual influence between two or more systems through various interactions (Y. Li et al., 2012). Nowadays, coupling is widely used in the study of climate change and the environment (Haughton & Hunter, 2004). According to (Feng et al., 2023), the calculation process to reveal the coupling coordination relationship between the site suitability of brownfields and the comprehensive urban functional demands is:

$$C = \frac{\sqrt{S \times D}}{(S + D)}$$

$$T = \alpha \times S + \beta \times D$$

$$CCD = \sqrt{C \times T}$$

S: Site suitability value
D: Comprehensive demand value
C: Coupling degree T: Comprehensive coordination index
CCD: Coupling coordination degree
($\alpha = \beta = 0.5$)

### 3.3.4. Matching relationship of site suitability and urban ecological demands

After calculating coupling coordination degree, quadrant division, which is a technique used to categorize data points based on their position within a coordinate system, is being used to assess this relationship between site suitability of brownfields and the comprehensive functional demand of urban areas. The x-axis represents the site suitability of brownfields for green infrastructure development and the y-axis is for the urban comprehensive functional demand. The coordinate plane is divided into four quadrants:
1. High demand–high suitability,
2. High demand–low suitability,
3. Low demand–low suitability,
4. Low demand–high suitability.

### 3.3.5. Prioritizing brownfields for green infrastructure development

The previous steps are followed by the process of identifying brownfields that have both a high degree of coupling coordination and a good location within the defined quadrants. In this study, the coupling coordination degree value must be greater than or equal to 0.85. This means the coupling coordination degree falls into the categories of “good coordination” or “high-quality coordination” indicating a significant level of alignment between brownfield suitability and urban ecological demand. The second condition is that the brownfield must be located in either quadrant “high demand–high suitability” or quadrant “high demand–low suitability”. This ensures that the identified brownfields are situated where there is a high demand for urban functions and either a high or low suitability for green infrastructure, as it can be seen in table 4.

Table 4 Matching degree/CCD value

| Matching degree / CCD value | High Demand High Suitability | High Demand Low Suitability |
|---|---|---|
| **Good coordination [0.85-0.90]** | Very High priority | Medium priority |
| **High-quality coordination [0.9-1]** | Medium priority | Low priority |

## 4. Results

The results presented in this section are derived from the application of the methodological framework. Site suitability and comprehensive urban ecological demand values are provided. Then, the results of the coupling coordination and matching degree are presented, illustrating the degree of integration between the site suitability analysis and the multifunctional green infrastructure planning methodologies. Finally, the section concludes with an illustration of the proposed prioritized brownfields, providing insights into their potential for green infrastructure development.

### 4.1. Site Suitability Value

Site suitability analysis was carried out for 319 brownfields (the Cartofriche dataset contained 416 sites, but 97 of these were deleted during data refinement). Seven attributes were selected according to literature background and study area. The weighted correlation between them was calculated using AHP methodology. The results of suitability values for the brownfields ranged from 1.64 to 4.52, while these scores varied, the general trend indicated favorable suitability overall (Figure 5). The analysis revealed that 115 brownfields, constituting approximately 36.05% of the total, had suitability values greater than 3.5. These brownfields were mainly concentrated near the Seine, close to the Rouen and Elbeuf municipalities and the surrounding area. There was no clear spatial pattern governing site suitability values, but brownfields located near Seine tended to be more suitable for green infrastructure development.

## 4.2. Comprehensive Urban Ecological Demand Value

The comprehensive urban demand value was derived through the integration of four criteria, each assigned corresponding weights. The determination of these weights has been accomplished utilizing the AHP methodology, with the detailed maps of each indicator provided in the Appendix. These values serve as indicators of the demand intensity for various urban functions within brownfield areas, ranging from 1 to 4.96. According to Figure 6, the distribution of brownfields on the basis of their overall urban demand scores is as follows: Brownfields with values between four and five comprise 31 sites, representing 9.7% of the total number of brownfields. In addition, there are 71 brownfields with values between three and four, representing 22.2% of the total.

Figure 5: Map of the site suitability values of brownfields for green infrastructure development

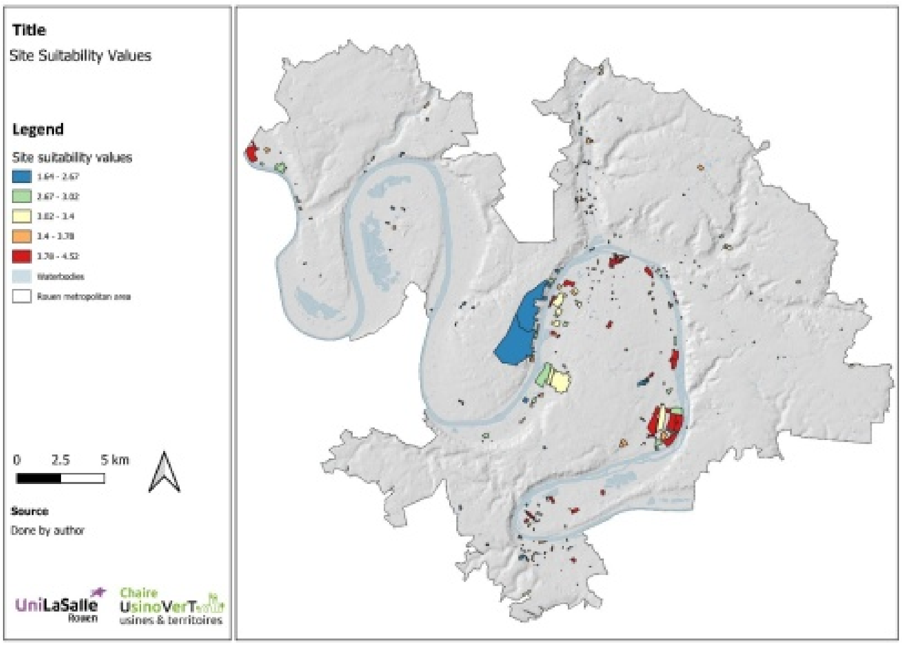
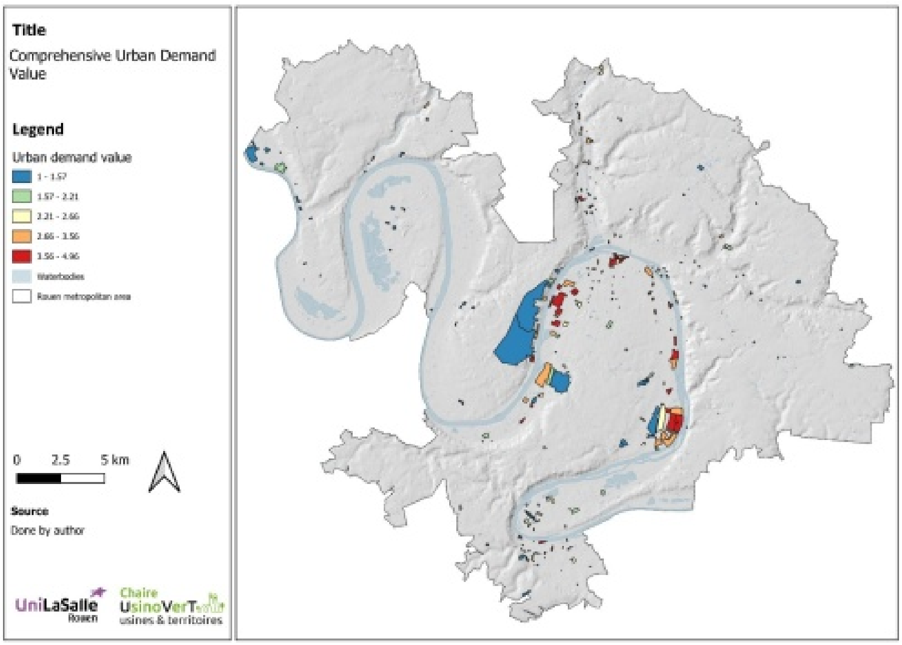



Figure 6: Map of the comprehensive urban ecological demand values for green infrastructure development




## 4.3. Coupling Coordination and Matching Degrees

The coupling coordination between site suitability and urban demand values range from 0.50 to 0.95, indicating an almost ideal coupling relationship between them. According to Figure 7, fifteen sites show high quality coordination, and 74 and 127 sites show good and primary coordination, which together represent more than two thirds of all brownfields. The highest coupling coordination degree is observed predominantly among sites located in close proximity to densely built-up areas, particularly in the alluvial terraces close to the Seine and tributaries. This spatial pattern indicates a harmonious trend between the suitability of brownfields and the ecological demands of the surrounding area.

The matching relationship between site suitability and urban functional demand is classified into four quadrants based on median values. The median values for site suitability and urban functional demand are determined as 3.23 and 2.41, respectively, using the natural breakpoint method. In Quadrant "High demand- High suitability", there are 82 brownfields, comprising 25.86% of the overall total. Quadrant "High demand- Low suitability", hosts 69 brownfields, constituting 21.76% of the total. When considering the high-demand regions, the total count reaches 151 (Figure 8).

Figure 7: Map of the coupling coordination degree

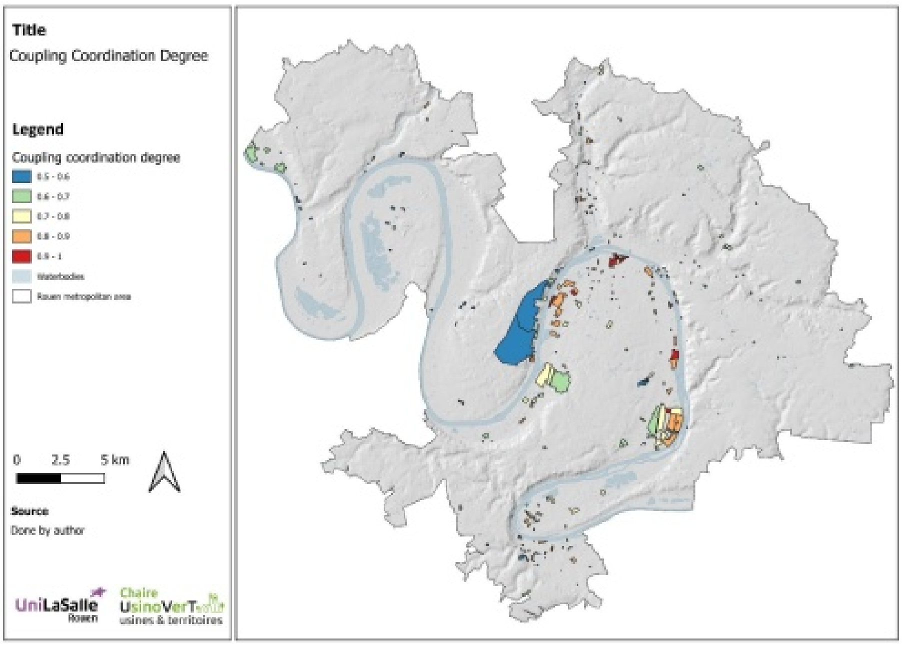
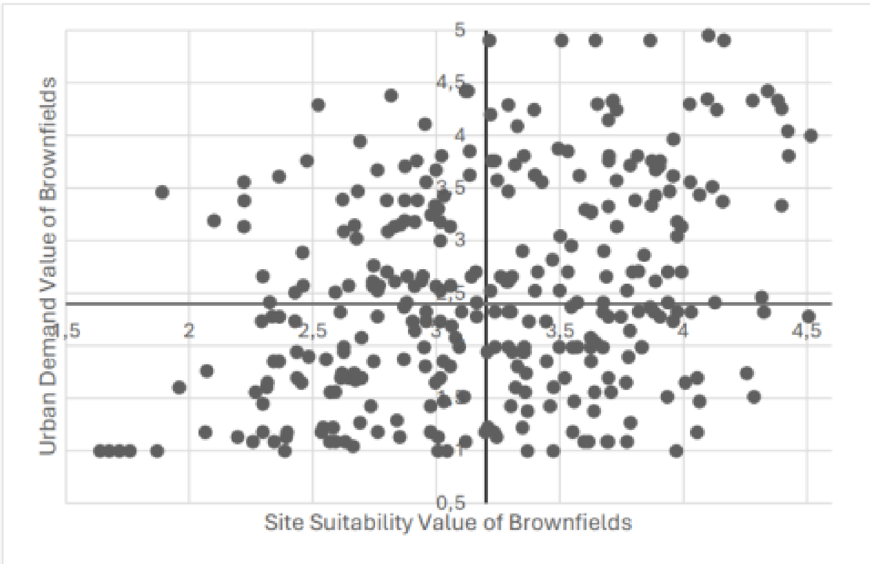


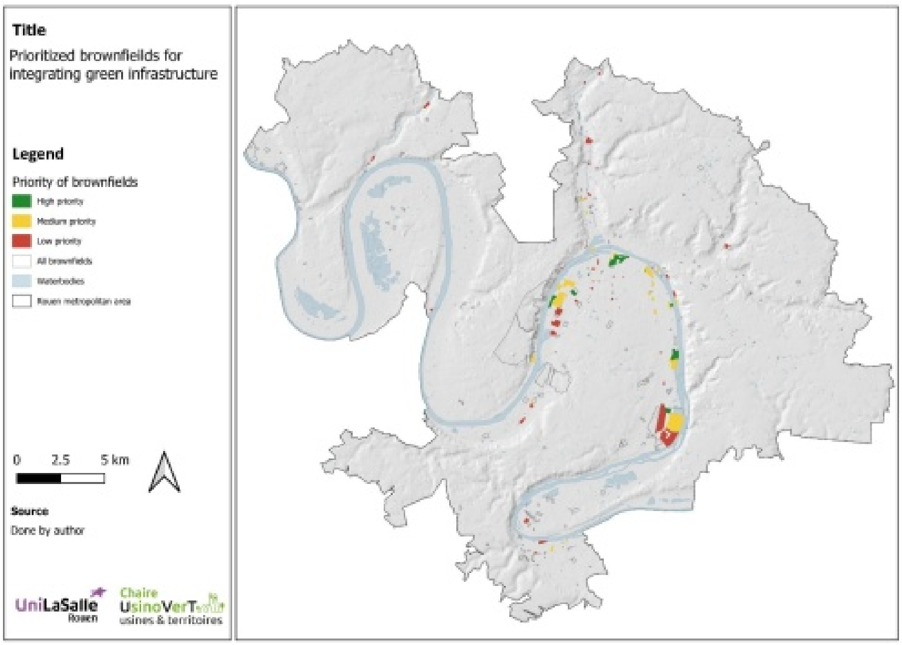

Figure 8: The matching relationship




## 4.4. Prioritized Brownfields

As a result, 84 brownfields were chosen to integrate into green infrastructure in Rouen metropolis. These brownfields were selected based on having high site suitability and high urban demand values, while having a coupling coordination degree (CCD) greater than 0.75. The brownfields with high site suitability and high urban demand values were categorized into three priority levels based on their coupling coordination degree. Specifically, 15 brownfields were identified as high-priority sites, having a CCD above 0.9. In addition, 28 sites fell into the medium priority category, with CCD values between 0.85 and 0.9, while 41 sites were classified as low priority, characterized by CCD values between 0.75 and 0.85. The spatial distribution of high priority brownfields interestingly shows an agglomeration of eight brownfields located in the Rouen city, in the industrial zone of the left bank. The other priority sites do not show a clear trend but are all located within the alluvial terraces of the Seine and tributaries.

Figure 9: Map of the prioritized brownfields for integrating green infrastructure




## 5. Discussion

The new approach in this study represents a shift from conventional methods by integrating site suitability analysis with multifunctional green infrastructure planning. The findings revealed a different perspective when comparing the results with site suitability analysis or multifunctional green infrastructure planning alone. For example, the range of site suitability values for high priority brownfields (15 sites) was between 3.50 and 4.51. However, assessing suitability in isolation led to the identification of sites (29 sites with a value above 4) that may not be strategically planned to address territorial issues. Similarly, the evaluation of comprehensive demand values for priority sites underscored the importance of considering the state of the sites. Although the urban demand values for the 15 priority sites ranged from 3.80 to 4.95, focusing solely on urban demand (30 sites with a value above 4) may overlook sites that lack the necessary suitability for green infrastructure development.
Furthermore, the importance of multifunctionality to maximize the comprehensive benefits of green infrastructure is emphasized. Previous studies often focused on a single functional demand (such as urban heat island), overlooking the broader range of benefits that green

infrastructure can provide.
Additionally, the Coupling Coordination Degree Model is a widely used method in environmental studies to determine the interaction and coordinated evolution of different systems, particularly in the Chinese literature. Numerous scientific papers have used the CCDM to integrate complex systems across a range of disciplines, demonstrating its versatility and applicability (T. Li et al., 2022; Y. Li et al., 2012; Shi et al., 2020; Tang, 2015; Xing et al., 2019) . Despite its widespread use and high citation rate in the Chinese literature, this methodology has not penetrated the academic literature of other countries to any significant extent. Our study sheds light on the effectiveness of the CCDM by demonstrating its utility in analysing the complex relationship between site suitability and urban ecological demands.
In this new methodology, it becomes clear that a high correlation between site suitability and urban ecological demand is not sufficient to fully meet the study's objectives. Despite a high correlation, certain brownfields have low values for site suitability and ecological urban demand. The quadrant relationship was used as a key tool to complement the model.

## 6. Conclusion

This study proposes a model to guide practitioners and researchers in identifying and prioritizing brownfields suitable for transformation into green infrastructure. The model provides a systematic approach for decision making to avoid random allocation and to save time and resources. The proposed methodology has been developed by overlaying seven key site attributes, including suitability of construction land, area, NDVI, slope, proximity to green area, proximity to settlement area and soil contamination levels, with ecological demand considerations as well as flood risk, high surface temperature, habitat fragmentation and air pollution. Through the application of the coupling coordination degree model and quadrant division, this study has facilitated the analysis of coupling and matching relationships between site suitability and urban demand criteria. As a result, the most suitable brownfields for transformation into green infrastructure have been identified.
A total of 84 brownfields were selected for integration into green infrastructure within the Rouen metropolis, with prioritization grounded in their high site suitability, urban demand values, coupling coordination degree, and matching degree. Among these, 15 brownfields were designated as high-priority sites, while 28 sites were categorized as medium priority, and 41 sites as low priority. The majority of these prioritized brownfields are situated in the alluvial terraces of the Seine river (left bank), offering significant potential to

contribute to the natural and semi-natural network of the region.
This research offers valuable insights that can inform the policymaking process regarding the redevelopment of local and regional brownfields. Its findings are not only relevant to the Rouen metropolis but also hold potential for application in other areas struggling with underdeveloped brownfield sites.
The current research needs further work in at least two aspects. On one hand, it is recommended for further study to investigate the application of the model between regions under the circumstance of different cities. On the other hand, in future research, socio- economic criteria will be collected to conduct a sustainability study on the relationship between brownfields regeneration and multifunctional green infrastructure development.

### Acknowledgements

The authors acknowledge the financial support of the Chair UsinoVerT-Factories & Territories, developed in a partnership between institut polytechnique UniLaSalle and Lubrizol, Rouen, France.

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