Nature in the city: a demonstrator of ecological transition

Research and innovation issues related to developing nature in urban areas

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Ecological Transition – Sustainable Cities Working Group

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Presentation and acknowledgements

Since 2020, ANRT has been exploring how research and innovation can contribute to tackling the climatic and environmental challenges that threaten our future on the planet. Following a conference on **life cycle assessments** on 10 December 2020,[1] an 'Ecological Transition' working group was set up in 2021. The group focused on the question of research needs to support the development of **recycling** in the construction and public works sectors.[2]

In 2022, at the request of the French Ministries for Higher Education and Research and for the Ecological Transition, the *Ecological Transition* working group turned its attention towards support for urban transitions through research and innovation, and adopted its current title of *Ecological Transition – Sustainable Cities* WG. In 2023, the WG worked on the theme of **circular and regenerative cities**.[3]

As a result, the WG is now part of the national and European ecosystem for research and innovation on sustainable cities, and takes part in:

— the Sustainable City Mirror Group, co-led by the French ministry for higher education and research (MESR) and the ministry for the ecological transition (MTECT), whose objective is to structure and coordinate the French community with a view to developing French participation in dedicated EU programmes;

— the DUT partnership (Horizon Europe), in an associate member capacity.

In 2024, the *Ecological Transition – Sustainable Cities* WG opted to reflect on the conditions for **developing nature in cities**, as a possible solution to deal with the climatic, environmental and social issues facing cities today. This working group gathered four times to listen to debates on the subject by experts and actors from the field (see annex 1).

The ANRT and the chairman Michael Matlosz warmly thank all of the speakers (appendix A), working group members (appendix B), and FutuRIS members for their support.
They would also like to thank **Anne Ruas (Gustave Eiffel University)** for her invaluable scientific advice to the WG, the Mirror Group for providing precious coordination and support to the ecosystem, the managers of Lab Recherche Environnement for supporting the WG's work, and the DUT Partnership, with particular thanks to the managers of the CUE *(Circular Urban Economies)* department.

The proposals put forward in this note are the fruit of working group presentations and exchanges in 2024. **The note does not engage the responsibility of the group members on either an individual or institutional level. It is driven by ANRT,** in its role as coordinator of collective exchanges and proposals aimed at those behind research and innovation policies.

For this reason, this note does not name the authors of quotes or the initiators of the projects mentioned: these quotes and examples were chosen to illustrate the ideas summarized in the note, rather than to convey any particular point of view expressed during exchanges.

1 Cf the web page of the conference, ANRT website.

2 *Pistes de recherche pour le développement du recyclage dans une dynamique circulaire,* Les Cahiers FutuRIS, ANRT, February 2022.

3 Organization of a day of international exchanges at the MESR on 1 June 2023, in partnership with the MESR, MTECT and ANR: *La ville circulaire et régénérative. Mieux valoriser les ressources des écosystèmes urbains : défis et perspectives [Circular and regenerative cities: making better use of resources from urban ecosystems].*

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Summary

"Learn from nature: that is where our future lies," said Leonardo da Vinci. Today, giving nature more room in our polluted, congested cities is a way of combining the practical with the pleasant in response to two major challenges: improve the health and well-being of increasing numbers of citizens; and react to the consequences of climate change, which have considerable impacts on cities (heatwaves, torrential rain followed by flooding, epidemics, etc.).

Nature-based solutions have emerged as innovative responses to a set of needs or systemic problems. In fact, the main strong point of nature in the city is its multifunctional character: it can bring multiple benefits to urban ecosystems, in terms of climate, the environment, biodiversity, health, etc. Encouraging the development of nature in cities has therefore become a key course of action for urban decision-makers.

What, then, are the conditions to ensure that this commitment to foster nature in urban environments has an optimal impact? And **how can research and innovation contribute to the development of nature in cities in the most appreciable and sustainable way possible?**

These are the questions raised by the working group during the four meetings devoted to this subject in 2024. To organize its reflection, the group opted to focus on three elements that constitute nature in the city:

— **air:** involving climate issues (in particular heat) and pollution;

— **water:** flows and networks; urban water management (especially rainwater);

— **soil:** issues concerning urban soils and subsoils, which are valuable substrates of the city as a whole.

The issue of **biodiversity** was treated cutting across these three elements.

Three key observations emerged from this joint reflection.

Firstly, **developing nature in urban environments is vital to ensure urban resilience and quality of life in cities.** It is a way to limit the different types of pollution resulting from the way cities are organized and function; adapt the latter to deal with current and future changes in the climate and environment; and mitigate their negative impacts at the scale of major planetary balances.

Next, **research and innovation can play a major role in this challenge of increasing the presence of nature in cities and integrating it better.** While it may be relatively easy to plant a tree, ensuring its survival in the mid and long terms is a lot more complicated: numerous conditions need to be considered that are particularly difficult in urban environments, and that require knowledge, skills, data and specialized tools. These requirements are even greater when trying to maximize the ecosystem services that 'nature' can provide to 'the city', taking into account the numerous interactions between each component of each of these vast realities. Successfully developing nature in the city is therefore anything but simple: it requires skills related to a large number of scientific disciplines, and innovation capacities coming from a wide range of stakeholders.

Lastly, **'effectively' developing nature in the city raises fundamental questions of a change in scale, and beyond that, of a paradigm shift.** Since, as far as nature is concerned, the conditions for 'living well in the city' are numerous and complex, its development involves embarking on a truly systemic reflection. And, as is often the case, the level of impact depends on the level of investment in the broadest sense: financial, temporal, cultural, etc. The current enthusiasm for urban (re)naturing is more about feeling good than about leading a green revolution. The benefits identified, however real, are in proportion to the as yet incremental character of initiatives. It is clear that if nature in the city is to contribute more to societal expectations (living better in the city, adapting to climate change, and mitigating that change), society will need to be ready to invest in this burgeoning movement. The difficulties of implementing the French Net Zero Artificialization (ZAN) policy illustrate this point. To achieve a more positive impact of nature in the city involves modifying the 'ecological' model to take on a philosophical, political, economic and social focus.

These three observations lead us to see **nature in cities as a genuine demonstrator of ecological transition, in its move from a complex system towards a new model,** with the support of research and innovation.

This working group mainly focused on the objective of making cities more sustainable, with a concern to conceive and rapidly implement a range of nature-based solutions. However, at several points the WG underlined the deeper, **transformative ambition** of developing nature in cities, and the need to make research and innovation part of this ambition.

* * *

Nature in the city is often put forward as a 'no regrets strategy': its multifunctional aspect means it can only improve what exists now. However, for that to be true, or in any case with a significant impact, it is necessary to respect specifications related to the huge heterogeneity of the realities concerned, which first assumes that they are known, understood, and quantified.
A large share of the research and innovation needs are thus concentrated onunderstanding and taking into account the key characteristics of nature in the city**,** in other words, its **variability in space and time** and its **complexity** (interweaving of ecosystems at all scales, diverse interconnections between its multiple components and with other elements in urban systems).

Three research and innovation avenues emerge from the WG's work (parts I, II & III)

The first avenue consists in **characterizing and modelling the multifunctional components of nature in cities.**
This involves improving our knowledge and understanding of these components; the WP focused on three: air, water and soil (including the subsoil). All three are characterized by the fact that their properties, the way they function, and their impacts are highly variable, depending on the local and/or time conditions in which they are analysed. Numerous questions, mainly related to matter, life, and engineering sciences, are raised here, regarding the physical-bio-chemical specifications of the three chosen components, the vegetation, and subterranean fauna, etc.

The **air** component raises significant challenges regarding managing heat in the city (urban heat islands (UHIs) and thermal comfort), as well as air quality issues. The challenges related to **water** have evolved over time, moving from a vision of urban water embedded in a sewage network to that of 'sponge cities'. Numerous nature-based solutions (NbS) have been studied by scientists and innovators, for example to regulate rainwater. The increasing scarcity of water also leads to other types of interrogation concerning its usage and management. Lastly, urban **soils** was qualified as 'uncharted land' by researchers and experts in the WG: while it has drawn increasing interest over the last few years, our knowledge of soil remains inadequate to answer questions regarding the composition and functions of this city 'layer', in particular as a substrate of urban nature.
Lastly, added to the intrinsic complexity of each of these elements, whose role and effects vary in time and space, comes the complexity of their **numerous imbrications:** nature in the city functions as a **system**, as seen by the case of vegetation, which requires nutriments from the earth, and water, etc.

These 'green' solutions for urban nature must also work hand in hand with so-called 'grey' (constructed, technological) solutions and 'soft' (socio-political, organizational) solutions: these three types of solution will have to be constantly rearranged to shape the cities of tomorrow.

The last example of the systemic challenges that constitute a challenge in themselves for research and innovation is the interweaving of the different levels of territories (sites, neighbourhoods, boroughs, cities, agglomerations, etc.), which make the city a puzzle with different dimensions.

As a result, *"comparisons remain difficult, and generalization is probably not achievable"*, according to one of the speakers. The aim is therefore to succeed in organizing sets of solutions corresponding to different contexts and use cases, based on data that are as numerous and reliable as possible, along with a definition of their relevance conditions. This therefore involves considerable **metrology, comprehension/qualification, and modelling challenges:**

— collecting data and ensuring its reliability,

— modelling and simulating, with a need to refine and integrate different models,

— opening and sharing data and models (key conditions for upscaling),

— characterizing and qualifying specific urban realities.

This raises the question of the skills available to undertake this work and to **transfer new knowledge and solutions to society.**

This is the object of the **second avenue of research and innovation,** which relates to the considerable innovation required to develop nature in cities: **how can we jointly build innovative solutions and decision-making support tools for this purpose?**
It is not feasible to wait for research to come up with all the answers to the numerous questions posed; urban actors (local authorities, developers, builders, right up to citizens) need to start preparing the ground for indispensable action. The requirement is to achieve the **best possible convergence between the complex reality and simple action.** This report develops two main orientations in this area and provides an illustration.

Promoting research in tune with the challenges and actors of urban innovation is of primary importance. Diverse avenues are possible: upstream and long-term collaborations between research and companies; explanatory documents (practical guides, technical fact sheets), etc. In addition, examples of tools and innovative solutions, currently being developed and disseminated, are proposed to accompany action and decisions on the field.

Second orientation: the **development of powerful, easy-to-use models,** which are two key conditions for usage in good, relevant conditions by urban actors restricted by scientific skill and time constraints. The key is to rank targets in order to find the right balance between relevance and simplicity. Thus, to be more relevant, these models must sometimes decorrelate dimensions formerly combined in the same parameter, while making it easier to take other dimensions into account. The example of an environmental digital twin illustrates the different aspects of this challenge.
More broadly, the innovation represented by **Technosols,** i.e. artificial substrates that behave like natural soils,[4], with specifications adjusted to the different planned uses, illustrates how research and action interweave to respond to the need to dispose of suitable materials for developing nature in cities.

These first two axes relate to the nature available in cities, and the conditions of relevance and efficacy. **The third research and innovation avenue** concerns the social demand for nature in cities: **how do we mobilize and equip the actors of regenerative cities?** Which social, political, legal, economic, etc. conditions will make society a favourable environment for developing nature in the city?

Although these questions were debated to a lesser extent by the WG, all agreed on the need to develop reflections in this area, in particular calling on human and social sciences. Several problems were mentioned, which can be grouped into three main categories.

Understanding and supporting the transformation of actor systems is a key lever to rethink, on the one hand, appropriate areas of responsibility and competence, and on the other hand, new means of interaction, corresponding more closely to the often cross-cutting challenges raised by nature in the city. The following emerge as clear subjects for both research and innovation: reviewing the external and internal frontiers of organizations, and their way of working; jointly creating urban nature with residents; ensuring a general improvement in skills in the urban ecosystem

Reinventing the frameworks and means of public action: beyond watchwords, the development of nature in cities is a powerful accelerator of dynamics that struggle to make headway in public policies. For example, it questions the major choices that preside over urban planning policies: what is the vision for cities, what are the priorities, what proportion of the means attributed guide urban changes and management? How do urban forms, in the very way they are designed, take into account the needs and opportunities of nature in the city?
Other, equally crucial questions relate to the capacity to get a multi-level government to work efficiently; to develop a high level of transversality between urban services; and to adapt regulations to accompany the development of nature in the city, with for example less-restricting thresholds to take into account the relative variability of some nature-based solutions.

Lastly, the **question of economic models based on full costs** is crucial to obtain a better shared vision of the costs and benefits of diverse actions to foster sustainable cities. While the direct effectiveness of 'grey' solutions has been demonstrated, we know that their negative externalities are often only partially taken into account; conversely, 'green' solutions with less massive impacts could be seen as more cost-efficient if their multiple co-benefits were considered. Whatever the case, decisions and action, both public and private, would gain from greater economic focus in terms of the investments required and the expected impacts. A lot remains to be done in this area, even though research is making progress, as shown by the example of work on evaluating the costs of restoring urban land.

To conclude, the cross-cutting question of **maintaining nature in cities** is the object of a specific focus (part IV).

It is well known that the initial production of an object is often valued more than its maintenance over time, just as an initial investment is valued more than the ensuing operating and amortization costs. Yet the proper functioning and sustainability of equipment are clearly highly important for users.

In terms of nature in the city, the maintenance issue is particularly crucial, since it ensures its very survival and conditions for regeneration. This issue also shows how the scientific, technical and social dimensions are interlinked.

Four aspects of the question of maintenance in cities are therefore examined:

— ***Philosophical and political issues***: what should the respective places of humans and nature be in cities? Should we nurture nature or let it be? Should we develop nature in cities, or rather develop cities with and through nature? In response to 'engineered' approaches, sometimes perceived as interventionist, ecologists observe that sometimes opting not to manage is also a form of management.

  Questions also arise concerning the means of collective choices: who decides on these questions, how, and on what basis?

— ***Scientific and technical questions:*** knowledge is still very incomplete regarding the levels and types of maintenance required for the successful development of nature in cities. For example soil and vegetation can lose some of their functions as they age, or become more polluted, even in the absence of pollution nearby. However, we still do not know much about the scope of the im-

4 The functions of soil include: habitat and support for biodiversity, regulation of substance and energy cycles (filtration, storage, transformation, etc.), production of biomass, support for buildings and infrastructures, source of raw materials, and archiving (conservation of information on natural and cultural history).

pacts of this ageing and pollution on the services provided and/or expected.

— ***Economic questions:*** we are still a long way from knowing how to evaluate, for example, to what extent it is economically preferable to leave nature to its own devices or to maintain it, taking into account the different costs, at different horizons, and the different options, in particular when including the different co-benefits (including the value of biodiversity or of nature itself) and the different ecological and social externalities.

— ***Socio-organizational questions:*** maintenance issues bring in stakeholders that are much more diverse than those involved in the initial production (including the actual users), with much higher collaboration stakes: who finances, who is responsible, who acts for what type of maintenance, bearing in mind that the benefits are multifunctional with numerous beneficiaries? These questions lead to reconfigurations of organizations and urban systems. New actor networks and new social practices can also be put in place centred on the functioning and evolution of 'relational infrastructures' that can be nature-based solutions (parks, ponds, etc.).

Introduction

"Cities are nature fashioned by man, in his image and made to resemble him", wrote one Canadian novelist.[5] Not a particularly flattering image, if you think about the problems afflicting cities: numerous types of pollution (air, water, soil, etc.), heat waves, flooding, social tensions, etc.

Without doubt, cities also have positive sides, both practical and pleasant. And they were probably no more healthy or enjoyable in previous centuries, although it is difficult to weigh up the balance between the progress made and the new or exacerbated problems resulting from urban development and climate change.

Cities must face up to a formidable challenge: that of meeting the basic needs (physical and psychological) of a constantly rising share of the global population, bearing in mind that:

— Urban population growth has an impact on living conditions in overpopulated cities;

— Climate change will considerably increase the pressure on these living conditions.

Cities are particularly vulnerable to climate change and its environmental and socio-economic consequences. The concentration of infrastructures and people in urban areas means that cities have more means to develop a degree of resilience; however, it has the dual effect of making them particularly vulnerable and amplifying problems, as shown by the example of 'urban canyons': streets flanked by buildings on both sides that absorb or send back heat rays, prevent cool breezes from circulating, and limit the absorption of excess rainwater and accelerate surface runoff, etc.

Numerous solutions are being developed to tackle these deleterious phenomena. They are generally ranked into three categories: **so-called 'grey', 'green' and 'soft' solutions,** respectively corresponding to technological, natural and socio-organizational solutions. For example, faced with a risk of flooding, solutions could include constructing a dyke (grey solution); removing waterproofing in some spaces to create floodable areas that absorb excess water (green solutions: draining ditches, wasteland, etc.); modifying land use plans to prohibit construction in some areas (soft solutions).

The WG's work focused on one of these three solutions, i.e. 'green' solutions (which can also include grey and/or soft dimensions).

Nevertheless, the working group underlined in a preliminary message the **need to combine these three types of solution to take a holistic approach:** none of these three categories is sufficient on its own to ensure a more sustainable city, in other words, one that is resilient to climate, environmental and socio-economic shocks in the future – and if possible, a desirable place to live for the humans residing there.
In addition, these three types of solution should be combined with a fourth type: sufficiency (*sobriété* in French), to ensure the indispensable reduction of anthropic pressures resulting from our means of production and consumption patterns.

Open definition of "nature in the city"

Numerous terms and expressions refer to the problem of making nature more present in cities. As we shall see, very different approaches can correspond to variable formulations of this problem. The WG tackled this subject in an open manner, by considering all of the conditions needed by a city that gives more room to nature. Concepts like urban renaturing, restoring nature in cities, nature-based solutions, and urban greening, etc. were therefore considered as different ways to express this problem, bearing in mind that when taking a more specialized perspective, they do not have the same meaning or scope, or take the same approach.

In order to determine a sufficiently precise field of analysis, rather than targeting a particular concept, the WG successively looked at three 'elements' of nature in cities during three specific meetings. Here, these elements are understood as 'proxies' for key urban issues:

— **air,** in particular related to **climate and pollution issues;**

— **water,** in particular related to **managing different urban water flows;**

— **land,** related to numerous **urban soil and subsoil issues.**

5 Jacques Gobdout, *L'Isle au dragon*. Seuil / Boréal compact, 1976.

Note that the reflection carried out does not claim to be exhaustive: numerous dimensions of nature in the city were not directly considered, such as urban agriculture, links between health and nature in the city, biobased materials, and biomimetic approaches.

Each of the three elements studied is currently the object of numerous scientific studies, many of which cross established disciplinary borders. Urban air, water and land are the focus of a great number of innovations, which allow an approach that is both respectful of their specific dynamics and more effective in terms of the ecosystem services provided. This research and innovation opens up new questions and potential solutions, which form the core of this report.

Nature in the city and adapting to climate change

Beyond the advances and perspectives concerning the three objects considered, a major observation emerged, which constitutes a first key message.

Increasing the place of nature in cities is a relevant, effective way to act in order to mitigate climate change, and in particular to adapt to it.

The mitigation issue can be summed up as follows: because cities are concentrated areas of human activity, which is a major source of climate change, limiting the human control of urban territories and leaving more room for natural dynamics would contribute (in a limited way) to reducing some of the causes of climate change.

In terms of climate change adaptation, the potential of nature in cities is particularly great. The box below shows several key figures regarding climate change and the need to adapt our urbanized cities.

> 6th IPCC report

* 2011-2020 decade: the hottest for around 125,000 years
* 2019: highest rate of CO2 concentration in the atmosphere for 2 million years
* Intermediate scenario (evolution at today's pace):

  + 2°C in 2050 at global level compared to the average from 1850-1900
  + 3°C in 2100 at global level

> Estimation by the Court of Auditors for France

+ 3.8°C in 2100 in France [estimation by the French Court of Auditors[6]]

Bearing in mind that a 3.5° increase by 2100 would lead to a loss in economic activity of 10 GDP points[7]

> Consequences (occurring now): rising temperatures with strong heat waves; heavy rain leading to flooding and flash floods; severe droughts; increased frequency and intensity of extreme climate events (storms, hurricanes, etc.); submersion of coastal areas; melting of the planet's permafrost and glaciers; increase in disease vectors (bacteria, viruses, etc.); higher death rate: heat,[8] natural catastrophes, diseases, etc.; loss of biodiversity in all natural environments; difficulties accessing drinking water, conflicts of use, etc. *"Climate change impacts and risks are becoming increasingly complex and more difficult to manage"* (IPCC report).

> From 2005 to 2015, the **number of towns exposed to high climate risks** increased by 131% (representing 16% of towns in 2015)[9]

> Excess cost of adaptation for the building sector: 2 to 5 % for new buildings and 10 % to renovate existing buildings, compared to no adaptation. This represents additional needs compared to the public and private investments required to reach carbon-neutral targets of **1 to 2.5 billion euros for new buildings and 4.8 billion euros for renovation.**[10]

6 « L'action publique en faveur de l'adaptation au changement climatique », *Annual public report 2024 – Summaries* - Cour des Comptes et Chambres Régionales et Territoriales des Comptes.

7 *Les risques climatiques et leurs coûts pour la France. Une évaluation macroéconomique. Summary. ADEME, November 2023.*

8 From 2015 to 2020, the estimated health cost of heat waves in France was between €22 and €37 billion.

9 Observatoire national sur les effets du changement climatique, *Exposition des populations aux risques climatiques.*

10 I4CE *(Institute for Climate Econnomics), Vagues de chaleur : ce que l'on peut dire des coûts d'adaptation des bâtiments,* June 2024.

The development of nature in cities offers numerous solutions in response to this enormous challenge of adapting urban environments to climate change. As a reminder, independently from climate issues, nature in cities is vital to maintain the balance of the urban ecosystem in general, and constitutes a key factor to improve the quality of life of inhabitants.

Nature-based solutions: effective multifunctionality

What are nature-based solutions, and how can they help adapt cities to the consequences of climate change?

The main nature-based solutions to adapt to climate change include urban greening, which involves planting trees and other plants in streets and parks, as well as greening roofs and walls on suitable substrates; and removing waterproofing from some areas, to restore functional soils that can absorb and retain heavy rainfall.

As an example, an ADEME (French Agency for Ecological Transition) report produced by TRIBU and CEREMA[11], lists the following eight solutions for urban cooling, detailing the conditions for contributing to combating heat in the city: parks, trees, lawns, prairies, green roofs, green facades, water bodies, rivers, and landscape constructions for managing rain water.

Four key arguments summarize what NbS can contribute to urban environments, and how they are presented as 'no regrets solutions'.

— NbS bring multiple benefits: each solution acts positively on a set of factors or problems. As an example, planting an urban area results in absorption of CO2, cools the air thanks to shading and evapotranspiration, develops biodiversity on the surface and underground, improves soil quality, contributes to human health and well-being (less heat, psychological benefits[12]), makes sites more attractive, and increases the economic value of neighbouring residences.

— Developing nature in cities is a course of action that is often considered as sufficient (or 'sober'), involving solutions that may be 'low-tech' and/or relatively inexpensive in terms of money, raw materials, energy, etc. The reality can be quite different: on the one hand, as we shall see, these solutions are not usually as simple as they may seem at first sight, in fact, far from it.

On the other hand, if the real ambition is to profoundly transform the city through and with nature, the investments will necessarily be higher.

Nevertheless, it is clear that the multifunctionality of NbS and the near-absence of negative impacts mean that they are particularly effective. This effectiveness will probably be judged to be even greater once we have learned how to better evaluate the total costs and benefits of the different types of solution: *"Classic accounting approaches do not always take into account the negative externalities of some grey solutions or the complementary advantages brought by NbS. This approach alters the comparison between NbS and so-called grey solutions, to the benefit of the former."*[13]

— Lastly, NbS are *"adaptative and reversible":* these living solutions are able to evolve according to local contexts and climate conditions, which are themselves changeable. In addition, they can develop *"in synergy with other existing actions, because they do not hinder the research or deployment of other solutions in parallel with their implementation."* [14]

For different reasons, *"nature in the city is likely to be a key factor in mitigation and especially adaptation to climate change"* according to ADEME.

Nature in the city: interlinked problems at different scales

'Planting trees' is the most obvious implementation of making nature in the city a solution for adapting to climate change. Many cities have announced plans to plant trees, seeing it as a concrete, simple way respond to ecological concerns that is appreciated by residents.

However, the WG's work has identified much more complex realities, in two areas.

Firstly, developing nature in the city is **not technically simple,** at least not sufficiently to reap the numerous expected benefits. For example, to ensure that a tree has a long, healthy life and contributes as much as possible to its environment, many conditions need to be considered and numerous difficulties overcome, thus raising a number of questions for research and innovation.

Next, that which is difficult at the scale of a tree, or when trying to find green solutions in a neighbourhood, becomes **extremely complex when aiming**

11 CEREMA, *Rafraîchir la ville. Des solutions variées,* ADEME, May 2021.

12 Note however that the benefits of nature in the city on human health require more complementary studies on the risks and disadvantages that they may bring elsewhere: increased allergies, development of vector-borne diseases, etc.

13 *L'adaptation au changement climatique et les solutions fondées sur la nature,* ADEME Stratégie, July 2024.

14 *L'adaptation au changement climatique et les solutions fondées sur la nature, ibid.*

at more in-depth, coherent integration of nature in the city. Recreating green, blue and brown belts in the city, interconnecting the needs of plants, water, land and air with those of humans and infrastructure, are challenges that require input from all types of science, and from all of the social forces working to organize the city and keep it alive.
The challenges involved in developing nature in the city can therefore either be tackled at the scale of its components (both human and non-human) or at the scale of the comprehensive system that it represents – and which does not boil down to simply adding up its components. The numerous interactions that make each urban territory a complex, specific world constantly require carefully adjusting all the dynamics that it comprises.

Seen from this broader perspective, the ambition of developing nature in the city takes on a whole new dimension: the city needs to go much further than simply making more room for nature, it needs to be **developed by and through nature**. This therefore raises a completely different challenge: that of a **different model**, based on making full-cost savings; preserving common areas; striking a new balance between science-technology-society relations to identify community benefits that are themselves then redefined based on new means; and establishing policy and legal regulations aligned with the objectives of an SDG-based ecological transition, broken down at the scale of the city, etc. All of these challenges obviously constitute **major research objects**, in particular for the human and social sciences.

These two levels of challenge illustrate the wide range of new knowledge and innovation needs required to develop nature in the city, depending on how incremental or disruptive the vision.

This observation underlies the work of the WG.

Both guest speakers and participants explored the highly detailed scientific questions that condition the viability and overall 'performance' of nature in the city. They also raised more fundamental questions concerning the complex connections between cities and nature, since these connections could usefully be analysed by science to put into perspective the diversity of human and non-human needs in cities.
This dual approach gives rise to the notion of nature in the city as a **'demonstrator of ecological transition'.**

This report presents these different dimensions of the WG's work. The group started by closely examining the first level of questioning mentioned above, which in itself comprises a great number of topics, and as the meetings went on, the second level emerged.

For the sake of clarity, this document is divided into four parts.

The first three parts explore work areas related to air, water, and urban land, from three different angles. However, it is essential to bear in mind that these three angles need to be worked on at the same time, since together they constitute the greatest challenge concerning nature in the city, which is intrinsically systemic. As a result, the fourth part focuses on a cross-cutting question.

I. **Characterize and model the multifunctional components of nature in the city** (challenges mainly related to the sciences of matter, life and engineering)
II. **From research to innovation:** jointly build innovative solutions and decision-making tools (challenges related to the move from science to innovation)
III. **Mobilize and equip the actors of regenerative cities** (challenges mainly related to human and social sciences)
IV. **Example of a key cross-cutting question: how should nature in the city be maintained?**

01 Characterize and model the multifunctional components of nature in the city

1. Complex realities that are different in space and variable in time

CHALLENGES RELATED TO URBAN AIR AND CLIMATE

Air in the city is a primary element that nature-based solutions can act on. Two key challenges are involved: managing heat in the city, and air quality in urban environments.

Managing heat in the city

Heat waves are putting increasing pressure on urban environments.

Two levels of perception and intervention can be identified.

— **City scale,** involving **'urban heat islands' (UHIs),** which result from the accumulation of heat in built-up areas. City air temperatures can be several degrees higher than in rural areas, with peaks up to 7°C greater, as observed in Berlin and Nantes.

— A **smaller scale,** i.e. that of the human body and its immediate environment (a small square, for example), where we measure the **thermal comfort**. This is influenced by numerous local factors: humidity, exposure to sun, presence of shade, circulation of air, clothes worn, etc..

Understanding how to manage urban heat requires employing a range of approaches and tools adapted to different scales and objectives in order to measure, simulate and model urban climate situations. However, as we shall see, all systems raise significant scientific and technological challenges regarding their **reliability**, due to **complex usage conditions calling for caution when analysing and interpreting.**

Urban greening is one solution to reduce heat in urban environments.

— **Trees** play a crucial role in reducing heat in the city thanks to the shade that they provide and evapotranspiration. At street scale, this effect depends on the density and layout of trees. A simulation by Météo-France showed that tree cover in 75% of free areas in Paris could reduce the city's temperature by 2.5°C during heat waves

— **Urban parks planted with trees** are usually cooler than built-up areas, but grass parks can sometimes be hotter than the surrounding area, in particular if they are not watered (the overall benefit is nevertheless greater than that of artificial areas). The size of parks is also an important factor: the bigger the park, the more cooling its impact, although only up to a certain threshold. Parks that have irregular, long shapes tend to have a lower cooling effect, while more compact parks, like in Gothenburg, lead to temperature reductions of up to 5.9°C.

— **Green roofs and facades** also contribute to reducing urban heat. The impact depends on the type of vegetation: the more 'intensive' a green roof is, with thick substrates and diverse vegetation, the greater the cooling impact thanks to the albedo effect – although mainly above the roof, with barely perceptible impacts at street and pedestrian level.

In general, the variability of the situations, solutions and their impacts is considerable, which opens up significant avenues for research and innovation.

Managing air quality and combatting urban pollution

Air quality in cities is without doubt a major public health issue. Air pollution, in particular fine particles (PM2.5), nitrogen dioxide (NO_2) and ozone (O_3), is responsible for numerous serious health issues, such as respiratory and heart diseases.

Although urban trees bring numerous advantages, they have a complex impact on air quality.
Their **positive impacts** on temperature and CO2 concentrations are well known, as are those of planted areas, often described as urban 'lungs'. For example, trees capture some particles and polluting gases on their leaves, which contributes to reducing the concentration of some pollutants in the air[15].
However, in urban areas, these positive impacts are counterbalanced by other, antagonistic effects, such as:

— Aerodynamic impacts: trees slow down air flows in the street, which can lead to an accumulation of pollutants emitted in the street, like NO_2 and soot. This increased concentration of pollution in the streets can have negative consequences for human health, in particular in high-traffic zones.

— Allergenic impacts: allergies to plants are exacerbated – and some plant species are more allergenic than others.

— Emission of biogenic volatile organic compounds (BVOCs): trees emit BVOCs, like isoprene and terpenes, in response to heat and light. These compounds can react with other pollutants to form fine particles and ozone, worsening air pollution. Emissions of these components vary depending on the tree species and are exacerbated by water stress, which underlines the importance of the choice of species in urban greening projects.

— Recent studies presented at the WG meetings suggest that in urban environments, negative impacts (pollutants impacting health, like PM2.5, NO_2 and O_3) are greater than the benefits.

Recent studies presented at the WG meetings suggest that in urban environments, negative impacts (pollutants impacting health, like PM2.5, NO_2 and O_3) are greater than the benefits.

In addition, although the subject was not directly considered by the WG, urban vegetation can also be responsible for an increase in vector-borne diseases carried by different animal species (ticks, tiger mosquitoes, etc.)[16].

Another important point is the indirect impacts of plants on pollution. For example, green roofs and facades optimize the use of cooling and heating systems in buildings, ultimately leading to lower energy consumption and therefore lower polluting emissions.

As part of the project ANR sTREEt[17], extensive studies were carried out to model the impact of trees on air quality in urban environments, taking into account their different thermo-radiative, aerodynamic and deposit impacts. These studies show the following **negative impacts on air quality:**

— Increased concentration of pollutants emitted by traffic, such as NO^2 and soot, of almost 5% on average, with peaks of up to 37% in streets with intense traffic.

— Increased concentration of ozone in urban backgrounds, and decrease in ozone concentrations in streets, with an average drop of 2.3% and a reduction of up to 23% in streets, following an increase in NO_2 concentration.

— Limited impact of dry deposits (deposits of pollution on leaves): average decrease of 0.6%.

— Increase in organic particles and fine particles due to BVOCs, especially during water stress periods.

These results suggest that the management and planning of trees, and more broadly of vegetation in urban environments, should be carefully studied (species, local conditions, etc.) to minimize the negative impacts on air quality. In particular, trees with large crowns should not be planted in streets with intense traffic, and species should be selected to avoid emitting high levels of BVOC (especially terpenes). Good urban greening practices can also limit allergenic effects.[18]

The effectiveness of these solutions requires a **detailed understanding of urban dynamics and the complex interactions between the different components of the urban environment.** Simulation and modelling tools need to be constantly improved and validated to provide decision-makers with reliable recommendations. In future, public policies should integrate this knowledge to ensure more resilient urban environments.

15 Note that this capacity to capture different pollutants is highly variable from one species to another and one pollutant to another. Also note that plants are effective screens against the dispersal of some pollutants, which limits the contamination of the environment (e.g. vegetation barriers along main roads).

16 See for example: Fournet Florence, Simard Frédéric, Fontenille Didier, « Villes vertes et maladies à transmission vectorielle : nouvelles préoccupations et opportunités », in *Eurosurveillance. Journal de surveillance, d'épidémiologie, de prévention et de contrôle des maladies infectieuses.* 2024 ; 29(10) :pii=2300548. https://doi.org/10.2807/1560–7917.ES.2024.29.10.2300548

17 ANR Street Project - impact of sTress on uRban trEEs and on city air quality – 2019-2024 - https://street.cnrs.fr/

18 https://renature.brussels/fr/actions/ville-saine/amenagez-en-reduisant-les-allergies-au-pollen

CHALLENGES RELATED TO WATER IN THE CITY

Changes in urban water management

Over time, urban water management has moved from a purely technical approach to a more holistic consideration of environmental and social problems.

Historically, urban water management was based on two core principles:

— **a large public network:** a universal model that aimed to provide equal access to the water infrastructure, seen as the symbol of urban development and the welfare state.

— **Water removed from its natural cycle:** water was managed in a linear manner, often disconnected from its natural cycle, treated solely as a resource or a threat, and mainly managed through grey infrastructures designed to accelerate its flow.

From the second half of the 20th century, this approach began to show its **limits**, with negative environmental impacts, increasing inequality, and saturated networks.
Today, urban water management aims to **reconnect the natural water cycle with urban ecosystems.** Hydrological problems are associated with other environmental, social and economic issues. Nature-based solutions attempt to make the city more resilient to climate events. They involve managing stormwater *in situ*, with a preference for infiltration and for creating 'sponge cities' capable of absorbing precipitation thanks to permeable surfaces and natural materials. Local authorities play a key role in this management, often working in groups of municipalities.

Nature-based solutions to manage water in the city

NbS act directly on the water cycle in cities by encouraging infiltration and water retention in the earth, and plant evapotranspiration, while reducing runoff on waterproofed surfaces. This limits the risk of flooding by reducing peak flows, slowing down the flow of water, reducing the volume of runoff and, in general, reducing the saturation of regular networks during intense rainfall.
Different types of water can be found in the city (river water, rain, wastewater, etc.), which require specific management that can be more or less integrated. In this paper, we mainly look at rainwater.

The conception and evaluation of nature-based solutions for managing urban water comprises three main phases: instrumentation, modelling and forecasting.

— **Instrumentation** involves collecting data to understand, document and evaluate the impact of NbS water on the urban environment. It covers a number of impacts: on ecosystems, taking into account restoration, infrastructure, and management and protection of environments; on thermo-hydraulic processes, which examine the interactions between heat and water on urban systems; and on biodiversity.

— **Modelling** employs the data collected to simulate how NbS behave in different urban scenarios. It can predict how effective NbS are in managing rainwater, mitigating urban heat islands and preserving biodiversity. For example, modelling the impact of a green roof or a rain garden can be used to compare these natural solutions with more traditional infrastructure, like concrete constructions. The models developed are essential to anticipate the effectiveness of NbS and to optimize their conception to take into account the specific features of each urban environment.

— Lastly, the **forecasting and planning** phase focuses on integrating NbS into long-term urban strategies. This systemic approach considers the multiple scales and complex interactions that characterize the urban environment. It aims to provide decision-makers with the tools they need to anticipate water management challenges, integrating thermo-hydro-mechanical processes and taking social, legal and institutional questions into account.

Numerous challenges in terms of knowledge and understanding

For these solutions to be fully effective, several scientific challenges need to be met. One of the main ones is **improving our understanding of the spatial heterogeneity of precipitation,** in other words, how rain varies in different parts of the city, **along with its temporal variability** (how precipitation can rapidly change, such as during a sudden storm). These aspects are essential to anticipate future precipitation and integrate the impacts of climate change into hydrological models.
Water infiltration and retention and evapotranspiration also raise challenges due to the heterogeneous nature of urban soils and vegetation, which influence the capacity to absorb water, and the evapotranspiration needs of different plants.

On a wider scale, NbS offer global benefits, like groundwater recharge and mitigation of urban heat islands (UHIs). However, to maximize these benefits, it is crucial to **understand the complex interactions between NbS and the whole water management system**, taking into account local differences. Although progress is being made in renaturing the water cycle, existing (and future) 'grey' infrastructures will continue to play a significant role.

Research and innovation challenges include improving our **understanding and anticipation of the impacts of urbanization and NbS on the water cycle,** and **clarifying the role played by soil, subsoil and vegetation** in the long term for water managed using these solutions.

Research can also actively contribute to **defining realistic strategies and trajectories** to implement NbS at urban scale.

In conclusion, as water is becoming an increasingly limited resource, it is essential to **prioritize the benefits expected from (re)naturalizing,** both at local and urban scales. This also involves exploring new approaches, such as using non-conventional water and separating excreta at source, to maximize the effectiveness of water resource management and reduce the environmental impacts.

NbS offer a promising option to tackle these challenges, but their success depends on the **capacity to holistically integrate them into urban management strategies.**

CHALLENGES RELATED TO URBAN SOILS

"Urban soils: uncharted land?" [19]

Urban soils are veritable reservoirs of biodiversity and key to the proper functioning of urban ecosystems and resilience. However, they are significantly threatened by development and urbanization: pollution and waterproofing deplete their natural environment qualities. Despite recent initiatives such as the French 'Net Zero Artificialization' plan, one speaker stated that, *"24,000 hectares of soil are artificialized every year. This means that we artificialize the equivalent of five football pitches per hour!"* The WG members pointed out that we still know little about urban soils and few studies are carried out, despite an increase in research during the last thirty years.

Multifunctionality requiring greater knowledge and understanding

Urban soils fulfil a number of essential functions. Urban pedology, involving the study of soils in urban environments, attempts to understand this multifunctionality, which comprises:

— **Carbon capture:** about 30 % of urban areas are planted, of which 70% comprise open soil. These soils can store up 7% of the national store of organic carbon, a proportion that is sometimes higher than that of the equivalent forest soils, although this capacity varies according to local conditions.

— **Stormwater management:** urban soils play a key role in the infiltration and storage of rainwater, helping to anticipate flooding and recharge the water table.

— **Plant production for ornamental, ecological, landscaping and/or food purposes.**

— **Preservation of biodiversity:** urban soils, in particular in planted areas like parks and gardens, can provide a habitat for considerable biodiversity: macrofauna, which is the most studied group (worms, caterpillars, etc.), and mesofauna (mites, ticks, springtails, etc.), microflora (bacteria and fungi), and microfauna, invisible to the naked eye (nematodes).

— Landscape, cultural and recreational **uses and values.**

Human activities have become a dominant factor in the formation and evolution of urban soils, leading to the concept of **anthropological sequences,** where soils mainly evolve in response to human intervention. Contrary to popular thinking, not all urban soils have deteriorated. In reality, a large variety of soil types exist in urban environments, which can be grouped into several categories according to their degree of modification:

— **Natural to pseudo-natural soils (only slightly modified by human activities),** such as Luvisols in urban forests and Cambisols in urban farmed areas. These soils have conserved a large part of their natural functions.

— **Reconstituted or constructed soils:** Anthroposols employed in horticulture, with a high input of organic matter, or constructed Technosols, like green roofs.

Note that some soils that have been completely altered following construction work or filling do not totally enter into any of the aforementioned categories.

These anthropological sequences show the complex dynamics of urban soils. An analysis of Parisian soils from 1949 to 2017 showed that 36% of the surface area of the Parisian agglomeration had changed allocation in 70 years, mainly as a result of urbanization.

Diversity that is both vertical and horizontal

The variability of urban soils can be seen in both their depth and their surface areas:

— Vertically, soils are made up of **superposed layers, known as 'horizons'**, going from the bedrock to the surface, each with specific properties and evolutions.

— Horizontally, the diversity of urban developments (underground and on the surface) leads to a **high local variability in soils and their functions:** in the space of a few metres, soils can be very different from each other over the entire area of the city.

Urban soils therefore require specific approaches to maintain or restore their functions: removal of waterproofing, decompaction, amendment, construction, etc. Due to their complexity and diversity, research needs to be developed to better understand the connections between the state of soils, their eco-

19 Title of the presentation by Christophe Schwartz (INRAE – University of Lorraine) – WG meeting on 17 June 2024.

logical functions and the ecosystem services that they provide, and test out solutions on the field to develop decision-making tools for public and private administrators.

SYSTEMS, SYSTEMS OF SYSTEMS: WHICH INTERACTIONS, WHAT FUNCTION?

The systemic approach, which is essential to gaining a pertinent understanding of the issues involved in fostering nature in the city, can be illustrated through three examples of interactions: between the three dimensions studied; between nature-based approaches, technological approaches and socio-organizational approaches in the broad sense; and between territory levels.

Interactions between urban air, water and soil

Air, water and soil work closely together in cities, following complex regulations depending on the parameters of each local and temporal situation.

As we have seen, the development of **urban vegetation**, for example, has direct yet complex impacts on air quality, urban heat, and the regulation of stormwater – without counting the cultural, psychological and social impacts for city residents.

In addition, urban soils play a crucial role in the management of stormwater and the success of revegetation. Artificialization of the ground prevents the natural infiltration of water, leading to greater run off that can cause flooding. Revegetation, in particular using techniques like rain gardens and green roofs, can improve infiltration while reducing the quantity of rainwater that reaches the sewer network. Healthy urban soil that is well maintained and rich in organic matter fosters more resilient vegetation that is more resistant to drought and torrential rain.

Another interaction example is between **air (urban heat) and soil:** *"Urban development is starting to modify the temperature of the subsoil. There are underground heat islands in towns, whereas often the subsoil has a cooling action, and in the future, we will really need cooling."*

The air, water and land aspects in urban environments are therefore closely interconnected.

Interactions between green, grey and soft approaches

Nature-based solutions are insufficient to compensate for human ravages in cities; it is therefore indispensable to combine them with so-called technological (or 'grey') solutions, and solutions related to human organization and behaviour ('soft').
For example, revegetation cannot compensate for greenhouse gas emissions from the three main contributors, i.e. **buildings, mobility, and food**. Managing the three dimensions of nature in the city, i.e. air, water, and soil, must therefore **go hand in hand with levers for action related to these sectors**. It is obviously preferable to find synergies, such as in the case of urban agrivoltaics.

Nature-based solutions such as creating green roofs and facades or urban parks, and restoring waterways in cities can, for example, reduce atmospheric pollution, regulate temperatures, and limit flooding and heat waves. For a sufficient impact, however, they generally need to be combined with **technological solutions**. Thus, to efficiently manage intense rain episodes and reduce the risk of flooding, urban drainage systems can be optimized by installing retention basins, underground reservoirs, and innovative water treatment plants. Ambitious renovation of old buildings is also essential to adapt cities to the future climate and ensure sufficient comfort indoors, avoiding a surge in energy consumption for cooling (air conditioning).

Lastly, **'soft' solutions**, such as adapting behaviour, sustainable urban planning, and the implementation of suitable public policies, are essential to guarantee the long life of initiatives. For example, raising inhabitants' awareness about responsible water management or the reduction of polluting emissions can make NbS and technological solutions more effective.
The combination of these three types of solution creates a system of complex interactions where each approach strengthens or completes the others. A resilient urban ecosystem is based on balancing these different solutions. The pertinence of the different solutions and their combination should be evaluated on a case-by-case basis, in line with the territory concerned.

Interactions between levels of territories

The interactions between urban realities must also be thought out at different levels of territory: from buildings to islands, neighbourhoods, cities, and even urban regions. But each of these levels introduces diverse, interconnecting urban, natural or human components. For example, the issues of managing urban heat, as seen above, are not the same for UHIs (urban heat islands) as for thermal comfort.

The question of **urban belts** provides a good illustration of these emerging issues of interconnecting the different scales of the city.

> At parcel scale, each green area, garden or water point plays a crucial role in local biodiversity, offering habitats for flora and fauna. These areas must also allow the **circulation of species and resources, while remaining connected to neighbouring areas.**
> At neighbourhood scale, creating ecological corridors: tree-lined streets, green facades and urban waterways allow species to move and co-

lonize new habitats, thus strengthening the ecological resilience of the neighbourhood.
At city scale, it is important that urban planning documents guarantee this ecological continuity by integrating these **green belts** (parks, urban forests, alignments of trees, etc.), **blue belts** (aquatic environments: rivers, lakes, basins, etc.) and **brown belts** (soils and subsoils with a capacity to support biodiversity). Urban infrastructures, such as roads and buildings, can be conceived or adapted to minimize breaks in these belts, for example, but including passages for fauna or by planting the roadside.
These belts also have a vocation to **fit into regional ecosystems**, since the city is a link in a much vaster ecological network, for example upstream and/or downstream of rivers, connected agricultural and forest areas, etc.

The development of nature in the city therefore requires a **resolutely systemic approach**, integrating not only the specific features of urban environments (air, climate, water, soil), but also the interactions between these dimensions, the types of solution deployed, and the territorial levels.

This holistic vision calls for extending and interrelating numerous types of knowledge at different scales. In this area, note that **the knowledge already available is highly heterogeneous:** some areas are better known than others, which calls for targeting efforts on the latter. A few examples follow.

— The **'pedology – soil science' discipline** has therefore been officially classed as a rare discipline by the French Ministry of Research.[20] In particular, little is known about the very rich biodiversity of urban soils: 25 to 60% of terrestrial species are present in soils, but only 1 to 3% of studies on urban soils consider this biodiversity.

— Concerning revegetation processes in cities, a key question is the management of the different plant strata: herbaceous, bush, shrub, tree strata, etc. Yet, as one guest speaker pointed out, *"many scientific studies centre on trees, the way they function, the species, etc., but few look at the **other strata, the soils and subsoils**."*

Other phenomena also merit further exploration, such as **evapotranspiration processes**, the **conditions and impacts of urban revegetation, urban ecological belts**, etc.

Faced with this considerable complexity of the components of nature in the city and its development, a key issue is improving our understanding and **more completely and precisely describing the way that these different components function and interact in diverse conditions.**
Significant measurement and analysis efforts are therefore required.

20 Ministry of Research - Note by the Coordination Service for Higher Education and Research Strategies, 21 January 2023.

2. Expanding and improving knowledge: metrology, modelling and qualification

Metrology specialists know that temperatures can vary considerably within 1 or 2 metres, according to local conditions. However, **the community of researchers and experts involved in this area is still very small, while the measurement and simulation needs are growing.**

"Societal needs have changed, new questions have emerged. As a result, the starting data aren't rich enough, with for example information gaps on production conditions, leading to approximations that don't respond to current needs. But the competencies available are still too limited to deal with this need for more specific, more numerous, better exploited data."

COLLECTING MORE DATA AND IMPROVING THEIR RELIABILITY

Collecting data in urban environments is made difficult by large local and/or time variations in environmental conditions. Measurements of parameters like temperature, humidity and air quality can be influenced by factors like shade, wind, the presence of vegetation, and surface materials, which make individual measures potentially unique and not representative of the wider picture. On the other hand, the composition of soils, which are less sensitive to time variations, can be very different a few metres apart.

The question of **methods and tools for collecting data** is therefore crucial. Concerning urban heat, for example, multiple, diverse sensor systems, which may be stationary or mobile, are necessary to capture a variety of local conditions, at different scales. Mobile measures, for example, can be carried out:

— at the thermal comfort scale: for example a backpack system worn by someone on the move (Cityfeel by Hepia, in Switzerland) or in a woven basket (CityClimateX[21]) ;

— at UHI scale: in a car (Thermoroute system by Cerema) or on a bicycle (example of a measurement campaign at the University of Dijon or Jean Moulin Lyon 3 University).

Firstly, installing and managing stationary measurement stations is often complicated in urban settings: administrative procedures involving a range of intermediaries (municipality, Bâtiments de France, land owners, etc.), and the need to protect instruments from curious passers-by and damage, etc.

In addition, *"**measuring is never obvious, immediate and direct:** you never directly measure what's*

21 www.cityclimatex.com

just under the sensor, you measure the impact of an environment, of a set of sources that it isn't always easy to identify," depending on the wind speed, for example.

The **period studied** should also be carefully considered: even if it is chosen in a coherent way (e.g. the same two summer periods over two successive years), the results can be influenced by situations that do not represent an average standard reality: measurement campaigns carried out during one summer are difficult to compare with those done the next summer.

The two ways of countering these limits are clear.
On the one hand, **a large number of local measures carried out coherently and pertinently *in situ*** is essential.
On the other hand, analysing the results, for later usage, requires a **high level of specialization** in order to interpret them with the required level of skill and rigour: taking into account the limits of relevance, correction of bias, etc.

In addition to measurements using on-site sensors, **remote detection** using satellite images and infrared thermography can be used to analyse urban areas and identify zones particularly exposed to heat. However, these methods, after processing that requires knowing the emissivity of all surface materials and the atmospheric parameters, only give access to surface temperatures, which do not directly reflect the ambient air temperature. For example, bitumen on a road can reach very high temperatures without indicating the temperature of the surrounding air. In addition, *"for a 5% error on emissivity (characteristic of the emissions from a material in infrared), you can end up with differences of 15%!"*. The margin of error is therefore considerable.

Due to these numerous limits or points of vigilance, one speaker went so far as to consider that, *"you can get a measurement to 'say' what you want by adjusting the way you measure"*. It is therefore necessary to propose rigorous protocols.

Increasing the quantity and quality of data is thus a first step forward. The next one involves constructing and using effective simulation and modelling tools.

MODELLING AND SIMULATION: REFINING AND INTEGRATING SCIENTIFIC MODELS

Once the data have been collected, they need to be employed to support a vision of urban realities and their interactions that is as comprehensive as possible, thanks to effective modelling and simulation tools. In a more operational perspective, these methods can also be used to **test and pilot the planned evolutions.**

Computer modelling is thus a valuable tool for simulating how different urban developments will impact temperature.

Example :
At a small scale, a tool like **SOLENE-Microclimat**[22]**,** developed by the CRENAU laboratory (Ecole supérieure d'architecture de Nantes) and CEREMA, can be used to simulate the impact of air conditioning on the heating of facades and the surrounding environment, and, in turn, the impact of this heating on the performance of the air conditioning.
Simulations show that emissions from air conditioning units on facades can increase temperatures by 2 to 3°C, which leads to a 10% increase in the cooling needs of buildings.

At city scale, the TEB (Town Energy Balance) model by Météo-France, which considers urban areas in meteorological simulations, can for example be used to simulate the impact of revegetation (green roofs, lawns, trees) on UHIs.

Another modelling solutions consists in employing **geostatistical models**. These have the advantage of using field observations to transcribe the thermal comfort or air temperature for a territory.

Example :
Lucille Alonso's PhD thesis (2021)[23] highlights the advantages and disadvantages of adopting this kind of approach. It also underlines the geostatistical errors that can occur depending on the urban morphology and field measurements.

However, **current modelling has limitations that are also challenges for research and innovation.** Four are worth mentioning here.

Firstly, building materials are not considered in enough detail: a dense concrete surface is considered as a porous concrete surface.

Next, **some dimensions are absent or insufficiently present in the conception of models.** For instance, urban trees are not systematically considered in air quality models, which hinders the precision of simulations.

Example :
The ANR project **sTREEt** *(Impact of sTress on uRban trEEs and on city air quality),* financed by the French research agency ANR (2019-2014), aims to fill this gap by studying how the stress of urban trees impacts air quality. The parameters include the aerodynamic effect of trees, the deposit of pollutants on leaves, and the emission of volatile organic compounds (VOCs).

22 Tool. https://solenemc.hypotheses.org

23 Lucille Alonso. 2021. Thesis (in French) on the interest of modelling air temperature associated with the need to characterize territorial vulnerabilities for a systemic comprehension of the risk of high temperatures in urban areas for Lyon and Tokyo. Jean Moulin Lyon 3 University. https://theses.fr/2021LYSE3008

Another example is the **lack of dynamic vision** in microclimatic analysis models or models of urban air quality, which are often based on static thermal data; greater consideration of aeraulic dimensions is preferrable.
More generally, city-specific climate models, and especially models of the future climate, are still largely insufficient. As one speaker pointed out, *"A great deal of work needs to be done first to define the climate of each city; and every city will have a different climate in the future. The choices that we make today need to be compatible with both today and the very long term. An important scientific challenge is therefore qualifying the climate of cities in 2050 and 2100. But in many places in France, what's difficult is getting hold of climate data."*

Next, **some dimensions are today integrated into models in an over-aggregated way**, which makes it difficult to obtain a sufficiently detailed vision of the realities considered. Models therefore need refining, by **decorrelating the components of these dimensions**, in order to better understand how each factor contributes to the urban microclimate and more widescale effects like UHIs.

> Example :
> The relation between solar radiation, evapotranspiration, and surface temperature is often modelled in an aggregated manner, which can mask significant variations and complex interactions.

Lastly, interactions between the different urban elements (air quality, climate, and urban hydrology etc.) often require **combining several models, for a sufficiently integrated analysis of the impacts observed or sought.**
Thus, coupling soil-plant-atmosphere continuum models (to simulate interactions between trees and their immediate environment) with urban climate and air quality models (like TEB and MUNICH) improves our understanding of the global impact of trees on a city.

> Example :
> The PhD thesis by Alice Maison (CEREA-Ecole des Ponts ParisTech), supervised by Karine Sartelet, aimed to quantify the different effects of trees on air quality in Paris: thermo-radiative effects, aerodynamic effects, pollution deposits on leaves, VOC emissions.
> *'Modélisation des impacts des arbres sur la qualité de l'air, de l'échelle de la rue à la ville" [Modelling the impacts of trees on air quality, from street to city scales] – Thesis defended on 28 November 2023, at the Ecole des Ponts ParisTech.*

VALIDATING MODELS: MOVING TOWARDS NORMS AND STANDARD PROCEDURES

The validation of models is a critical aspect that is often underestimated in urban research. In the absence of rigorous validation, the results of simulations remain uncertain and can lead to inappropriate recommendations, resulting in counter-productive action.
Validating a model involves ensuring that the simulations produced are in line with the actual data observed. However, **no universal norms exist to validate urban microclimate models,** which makes it difficult to compare studies and assess the reliability of models. Unlike models of heat in buildings, which follow internationally recognized standards, micro-climatology models lack clear standards. The International Energy Agency is attempting to fill this gap by working on specific annexes, but these initiatives are still being developed.

The creation of **benchmarks** is a first stage to standardize the validation of models. These benchmarks can be used to compare the performance of models in controlled conditions and adjust them in line with the results obtained.

> Example :
> **The DIAMS project** (diagnosis, design and management of urban overheating during heat waves: cross-fertilization of microclimatic simulation tools and IRT imaging), coordinated by CEREMA and funded by the ANR, aims to evaluate the contribution of satellite thermal infrared imagery to simulate urban microclimates in order to assess urban overheating.
> One part of the project therefore focuses on **qualifying the models** developed or used by the consortium on the basis of selected datasets. The results of microclimatic simulation models at district scale were **compared** with each other and with the experimental data selected for various case studies.

The establishment of norms and standards for a reliable comparison of results in different urban and climate contexts is another domain in which research can make an active contribution. However, to ensure that benchmarks are useful, researchers need to share their data more openly.

OPENNESS AND SHARING: IMPACT LEVERS TO MOVE UPSCALE

Sharing data and comparing tools between researchers, urban planners, public decision-makers, companies, etc. are essential to develop relevant models for piloting the development of nature in cities. **Insufficient sharing of data is a common problem** in environmental research. The availability of quality data is nevertheless essential to validate these models, compare the results, and develop robust solutions for general application. Initiatives such as open data platforms and collaborative research platforms are means to promote this sharing culture.

> Example :
> Concerning urban stormwater management, data on the performance of nature-based

solutions such as green roofs and retention basins are often limited to specific case studies. **The Multi-Hydro model** developed by Ponts ParisTech, which combines 4 existing modules (precipitation, runoff, infiltration and treatment), can be used to simulate the impacts of these NbS on stormwater management at the scale of a district or city. It has also been coupled with the microclimate model SOLENE-Microclimat as part of the ANR EVNATURB[24] project. However, for this model to be useful, it needs to be **supplied with reliable data from different cities and climate contexts.**

CHARACTERIZING AND QUALIFYING EMERGING URBAN OBJECTS

Beyond the data question, wider questions concern the **characterization of urban entities that are still insufficiently understood.**

The ambition to manage a number of urban elements in a more sufficient, responsible manner leads to the observation that it is necessary to consider them more attentively and to know more about them. Questions range from the **designation** of these entities (definitions, semantic issues, etc.) to their **characterization** based on a variety of dimensions: contours or perimeters, content, evolution, interactions with other elements and their impacts, etc.

— First example: **'open ground'**, which common sense associates with the idea of non-artificialized earth in which certain trees might be planted in cities for example, raises numerous questions that cut across several disciplines. While the expression is increasingly used by urban planners and developers, ecology specialists tend to prefer the term **'living soil'**. The criteria for qualifying 'open ground' can be different: they might consider the absence of surface covering, the permeability, the horizontal continuity (brown belt) or vertical continuity (depth), the bio-physical-chemical quality, etc. – or all of those things, as suggested by an ecology specialist and WG member, who raised the following question:

> *"Should we have a dichotomic vision, with open ground in some places and not in others, or should we map out a gradient, with different levels of open ground in the city? We could therefore distinguish strict, deteriorated, partial, and absent open ground."*

The operational issues related to these questions are considerable. Urban planning documents are starting to include 'open ground coefficients', which comes up against the question of determining the optimal coefficient at district level. Since scientific studies on the question are still rare, some local authorities establish an arbitrary figure such as 20% or 30%.

— Second example: **urban wasteland**, which according to the ecology specialist mentioned above, constitutes a *'blind spot'* in knowledge of urban reality for several reasons, starting by its very definition.

• For urban planners, wastelands are urban areas that have not yet been developed;

• for ecology specialists, they are seen as a refuge for life, a natural space to be preserved in the city. Their properties and uses are also a source of debate, contributing to very different visions of the concept of nature in the city – a subject we shall return to.

— Final example: the notion of **'urban soil'** is conceived very differently depending on the discipline or profession. According to one speaker, we should **move from the notion of 'soil-surface'**, corresponding to the land-focused approaches of developers and urban planners, **to a notion of 'soil-matter'**, used by pedologists and agronomists, with the concepts of 'soil profile' being used by the former (soil available for vegetation and capable of providing a range of ecosystem services), and soil quality for the latter.

The **need to possess more solid knowledge bases to better qualify a number of urban realities** is reflected in numerous **semantic debates** in this domain. These point to the necessity to build a vocabulary for nature in the city, which is still at a very early stage. These terminology issues reflect different areas but also diverse, sometimes contradictory, approaches to the objectives and methods to employ. To give a few examples, terms like 'greening', 're-naturing' and 'revegetation', which are sometimes used interchangeably, involve different practices and ambitions.

24 https://anr.fr/Projet-ANR-17-CE22-0002

The concept of **'greening'** evokes a decorative, domesticated approach to nature, often accompanied by a non-negligible environmental impact in terms of consumption of resources like energy and water.
'Building greening' (green roofs and walls for example) is current practice, but should not be confused with **'renaturing'**. This term refers more to **restoration** of highly deteriorated areas, with an accent on recuperating the ecological functions of soil, which often – but not always – involves a return to a prior, non-artificialized state. However, this definition is not totally stable. For example, for the Zero Net Artificialization (ZAN) principle applicable in France, renaturing designates compensating for the consumption of artificialized land, a concept extended to include the de-artificialization of land by the Climate and Resilience Act of 2021. In addition, **ecological restoration** is not the same as **ecological rehabilitation:** restoration aims to return a site to its original ecosystem, while rehabilitation aims to re-establish a level of ecological functioning without necessarily restoring the site's previous state. These terms can overlap, in particular when talking of the **re-functionalization** of soil, which aims to re-establish ecological capacity without returning to the initial state.

Lastly, beyond definition questions, the progressive discovery of the complexity of forms and living interactions in urban environments generally calls for **extending knowledge on all of its components:** air, water, soil, fauna and flora. *"Improving the characterization of vegetation in and below cities with the development of urban tree inventories"* was thus crucial for one guest speaker.
The same goes for the other components mentioned: soils, etc. – and in particular, interactions between these components, and with other dimensions of urban life.

Acquiring more detailed knowledge to better understand and develop nature in cities is therefore a key issue.

To conclude, there is currently a clear need to **increase the quantity and quality** (data, knowledge, models, etc.) to respond to the challenges of the complexity and variability of urban realities.

At this stage, it is understandable to have an ambition to improve the reproducibility of results and solutions, and develop more generalizable methods, etc. Nevertheless, this ambition is probably unrealistic, in the eyes of one speaker: *"Comparison and generalization remain difficult.* ***It doesn't seem possible to generalize approaches; what we might be able to do though is to organize solutions in different contexts, once we've understood better how it works.*** *Which is why it's worth correctly establishing study tools, and measurement protocols".*

Adapting solutions to local contexts, taking into account the specific features of each urban environment, should in any case become the norm rather than the exception.

This is also the **ambition of European programmes**, which consider more diverse contexts. One speaker made a call to strengthen the connections between European programmes and national programmes, giving the example of the EU programme *Soil Health BENCHMARKS*, based on 24 multi-scale, multi-user cases to observe and manage urban soils: as a result, we can *"access cities with contrasting histories, climates, etc. in order to identify diverse use case categories."*

Note, however, that an **increase in quantity without an increase in quality would not be a pertinent response** to this need to better understand urban realities. As underlined by the above-mentioned speaker, **an accumulation of data is not in itself a sign of progress:** *"The results become even more complex, which doesn't necessarily make them easier to understand, and makes it even harder to take decisions."* In some studies, on parks for example, *"you find all kinds of results; in these conditions, it isn't easy to decide".*

The **increase in quality needed** therefore involves:

— enriching data with considerable information relating to their production, as pointed out by the WG chairman[25] ;

— greater collaboration and sharing of knowledge between all stakeholders (researchers, local authorities, companies, etc.);

— stronger validation of methods and models;

— more specialized, much more numerous scientific and technological skills regarding the characterization and comprehension of nature in the city.

25 Michael Matlosz, Lorraine University and the French Academy of Technologies – WG meeting on 19 March 2024: *"If the data aren't presented along with information about how they were produced, they aren't very useful, because the results can vary considerably depending on the production conditions: a sensor placed in a particular place or a metre away, the fact that it was sunny that day or not, or sunny in that particular place, etc. Without such information, collecting data might even be inappropriate since they risk being irrelevant."*

02 Jointly build innovative solutions and decision-making tools

1. Promote research in step with urban innovation issues

FRUITFUL COLLABORATIONS BETWEEN RESEARCH AND COMPANIES

The subject of nature in the city mobilizes the academic community on a spectrum ranging from the most fundamental to the most applied research. Numerous structuring partnerships exist involving companies or communities on research and innovation projects or as part of collaborative initiatives.

The challenges of establishing nature in the city constitute one of the current work areas of the Lab Recherche Environnement[26], which, as one of its managers observes, *"range from fundamental research to decision-making support, and include the development of tools and methods for operational personnel."*

The maturity of this research partnership is illustrated by the **'Research and Solutions' programme**. Instead of relying on researchers to propose the project themes and research, this programme is based on proposals made by staff at Vinci and its subsidiaries, who are invited to suggest R&D themes in line with the environmental solutions put forward by the company. For example, a PhD is being undertaken as part of the project on action against invasive species along the Strasbourg motorway bypass.

Through this type of partnership, research continually feeds into urban actors to invent new nature-based solutions, boosting the capacity of cities to deal with climate and environmental disruptions.
It is worth repeating something we already knew: these long-term, partnership-based studies are the best way to develop emerging subjects like nature in the city. They should be more widely supported with the ambition of achieving major sustainable development goals.

GREY LITERATURE AND PRACTICAL GUIDES ARE VALUABLE TOOLS

This partnership-based research produces results that can be very useful for urban actors. In their initial format (as publications, data, etc.), they are however only accessible to the most specialized. Outside this small circle, the scientific literature needs to be popularized to make it available to a wider audience.

One speaker, who is an ecology specialist at a regional agency, noted: *"For me, it's important to be able to draw answers from this scientific literature. It's rarely available to a wider public, and so there are still efforts to be made in that area: scientific responses exist that aren't implemented in urban action plans because there's no operational 'translation'."*

The speakers agreed: even if it still needs to be widely developed, scientific knowledge on nature in the city could and should be *"made available and accessible to all via operational tools and widely disseminated virtuous practices"*: methodological guides, technical sheets, operational kits, etc.

This 'translation' of science into knowledge and methods that can be adopted by urban actors is increasingly recommended as a key deliverable of re-

26 Lab Recherche Environnement stems from a Vinci sponsorship of three schools, active since 2008: Mines Paris-PSL, AgroParisTech and Ecole des Ponts ParisTech. Three additional areas of academic expertise were therefore brought together: energy and LCA of buildings and districts (Mines); urban ecology, food and microclimates (Agro); and transport and infrastructure (Ponts). Since 2008, this research chair has been developing programmes on the environmental performance of buildings, districts and infrastructure.

search projects. It is valuable to help users increase their skills by discovering the available tools and methods and the conditions in which they can be implemented.

For example, **the DESSERT**[27] **project**, run by the Sols et Environnement laboratory (Lorraine University / INRAE) and funded by ADEME, aims to shed light on waterproofing removal practices – which is a crucial part of the Net Zero Artificialization (ZAN) policy. A guide on designing operations to remove artificialization is due for publication in 2024 with the aim of disseminating good practices and guiding decisions made by urban leaders.

Numerous institutions have identified this need and propose resources that are as accessible and pertinent as possible. CEREMA, for example, has published its 'new editorial collections' online, broken down into five categories: references, dossiers, essentials, resources, and notebooks. In addition, a great number of laboratories, agencies, associations, foundations, and companies propose this type of concise, operational information, creating a bridge between the complexity of formal knowledge and the need for action with a call to 'learn as you go'.

INNOVATIVE SOLUTIONS CURRENTLY MATURING

Research also directly contributes to the production of solutions and operational tools. Numerous examples were provided during the WG's work.

Biodi(V)strict® : urban development support tool based on a scientific approach to evaluating biodiversity

This tool, produced by the Lab Recherche Environnement, is easy to understand for non-specialists, fast and inexpensive to use. It can be used to assess the biodiversity potential of a site to test out development scenarios. It is currently employed by a subsidiary of Vinci.
The partnership between the Lab's three partner schools and Vinci gave rise to Urbalia, a subsidiary of Vinci, based on Biodo(V)strict®. Urbalia acts at the scale of urban projects or islands, gathering all types of ecological engineering to work on all of the issues involved in urban biodiversity: ecological continuity, avoidance of pesticides on trees, etc., and then extend into landscape development and associated works.

EquoVivo : from tool to brand

EquoVivo is a brand created by Vinci Construction, gathering all of the knowledge accumulated by the company based on the 'avoid, reduce, compensate' model employed in major infrastructure projects. The brand proposes solutions involving ecological engineering, renaturing, restoration of waterways, re-establishment of ecological corridors, action to combat invasive species, etc.

Revilo: urban cooling solution

Revilo was developed by Eurovia (subsidiary of Routes de Vinci) with the University of Lorraine and AgroParisTech to work on urban heat islands. This Eurovia product goes beyond the manufacture of roads, squares, pavements, etc. to include soils, surfacing, Technosols, etc.

Graphab: modelling movements of species in urban environments

Graphab is a tool developed by the University of Franche-Comté that has been used by cities like Strasbourg, which employed the movements of red squirrels to model their networks and ecological continuity in urban environments.

REGREEN: identification of artificialized land to be renatured

The EU project REGREEN aims to identify artificialized areas for which a renaturing operation would result in significant ecological gain (improved soil functioning, etc.). It is a useful support when implementing the ZAN policy.

To sum up in the words of one speaker, *"Transforming scientific tools into operational engineering tools is really important. For us, as a research institute at an engineering school, it's clearly a research avenue in itself. The issues behind it are important: data become information, knowledge, comprehension, and ultimately, decisions."*
The objective is to **accelerate and change scale**, to successfully transform cities through nature so that they can tackle climatic and environmental challenges.

Among the levers identified, the question of a model adapted to urgent and complex operational uses appears central.

2. Develop powerful, easy-to-use models

As we have seen, the diverse range of data that need to be taken into account to characterize the components of nature in the city in varied environments has led researchers to develop scientific modelling that still requires considerable development. However, researchers are also solicited by consultancy companies, municipal technical departments, etc. to propose modelling that is **operational rather than scientific:** models are therefore decision-making aids to design, plan and support the implementation of projects to develop nature in the city.

27 DEsimperméabilisation des Sols, Services Ecosystémiques et Résilience des Territoires.

A key challenge is **striking a balance between complexity and simplicity:** how do you ensure that the models developed are capable of capturing the complexity of urban ecosystems, while remaining usable by non-specialists who are often constrained by tight political and economic agendas?

Researchers here work hand in hand with the city's technical actors (engineering consultants, companies, service providers, etc.), who connect research with the public decision sphere: local elected representatives, managers of public and para-public institutions responsible for urban management. These actors urgently want to get hold of modelling, simulation and decision-making tools that are sufficiently powerful to effectively take into account a large mass of complex, heterogeneous data, while meeting with the following specifications:
— easy to adopt;
— quick to use.

Note that this expectation of making 'adjustments' to balance complexity with simplicity is not just a technical question of adapting existing models: increasing operational relevance constitutes a **scientific problem** in itself, including for human and social sciences. What parameters and levels should be applied to these adjustments and how should they be done? These questions require significant research and innovation. For example, aspects related to local application and different ways of using the targeted solutions need to be treated taking an approach that is both thorough and modular.
Specialists, but few other actors, know very well that attempting to 'simplify' a model for operational purposes raises a whole new level of complexity – it is not simple to simplify! In fact, in some cases, the adaptation does not involve reducing complex issues to make them simpler, but rather moving in the other direction, by adding more modules to simple base models.

Feedback on experience and a number of examples illustrate the challenges raised by this quest to interconnect complexity and operational effectiveness.

DECORRELATING TO INCREASE RELEVANCE

While applicability to a particular context implies only taking a particular reality into account, it is nevertheless important to consider the **entirety** of that reality.

Thus, when taking into account the impacts of vegetation on air quality and health, the speakers underlined the need to *"improve modelling of plant varieties and their specific emissions"*, in particular those of volatile organic compounds, not to mention the effects of these emissions, and bearing in mind that plants also absorb some emissions and have other benefits. Numerous other dimensions also need to be taken into account to evaluate the benefits of developing vegetation in a neighbourhood. *"So you need to decorrelate everything; but how do you do it, and what global, conceptualized tool do you use? The scientific community doesn't seem to currently possess such a tool capable of processing co-benefits on comfort, heat, the dispersal and absorption of pollutants, emissions of compounds and atmospheric chemistry, the water cycle, building insulation, etc."*

ADJUSTING MODELS TO MATCH NEEDS

Choices need to be made in order to prioritize models' expected contributions.

This question guided the work carried out by Sonia le Mentec in her PhD[28] the objective of which was to design and validate a model to evaluate the impacts of revegetation in cities on the regulation of the microclimate and its contribution to improving air quality.
An initial inventory showed that *"a lot of models exist, and the more detailed they are, the longer and more complicated they are to use: one model, for example, needs to run for three days to simulate a day."* Since the PhD was carried out as part of a partnership with Vinci, *"a choice was made, in consultation with Vinci to produce a simple model"*, developed based on a Météo France model, in which the vegetation employed (soil-biosphere-atmosphere interaction) was replaced by a model developed by the host laboratory (SURFATM), integrating pollutant exchanges and heat exchanges.
After the PhD, the model was worked on by the laboratory for its own application purposes. *"The tool is still not developed enough to be handed over to the Vinci teams. We hope to do so in the next few weeks or months, as we did for the vegetation model, which is available now and quite easy to use,"* explained the co-supervisor of the thesis.

DEVELOPING A RANGE OF OPERATIONAL TOOLS

A number of companies are working on the design and provision of modelling solutions adapted to the emerging needs of cities, to support decision-making and action to develop nature in the city.

> **Ingérop**, a consultancy and engineering firm, has grouped its ecology and sustainable development activities into a subsidiary called **Actierra**, with the aim of making them clearly visible to its clients. Meeting with customers' expectations means providing them with evaluation tools and coming up with adapted solutions. *"But we can't use research models, which are very precise but take time: a month for a mock-up, and 15 days of simulation.*

28 Sonia Le Mentec, "Impact de la végétalisation sur l'îlot de chaleur urbain et la pollution d'ozone: quantification par une approche de modélisation à l'échelle d'un quartier" [impact of revegetation on an urban heat island and ozone pollution: quantification through modelling at district scale], doctoral thesis in environment science supervised by E. Personne, D. Flick and P. Stella, defended on 07.07.2022, Paris Saclay University.

The challenge is to obtain fast models (a few days at most) that are sufficiently reliable," explained the speaker from Actierra.
Based on the observation that numerous tools exist, Actierra is working on developing a methodical vision to use appropriately: ranking by cost, operational dimension, and the degree of spatial resolution, etc.
The company notes that tool requirements should be ranked according to usage: *"the need is for simplified tools for upstream studies, and then more comprehensive tools afterwards".* For example, concerning thermal comfort, the following tools are available in order of increasing complexity/comprehensiveness: Score ICU, ICETool, UMEP, SOLENE-microclimat, and ENVI-MET.
To consolidate its approach, Actierra launched a Cifre[29] PhD, which evaluated 13 tools to measure and simulate urban heat based on a set of criteria: spatial and time scales, simulation time, market availability, type of usage, type of results, etc. Some of them, like SOLWEIG, appear to be quite simple, although with limitations related to simplified parameters. Others are more advanced, e.g. ENVI-MET, which: *"can't be handled by everyone, you need to understand the way it considers physical phenomena. The computing times are longer. And the model hasn't been validated either. You need a certain level of expertise to use this model properly."*

Learning how to design and handle pertinent models to support decision-making and action is a common challenge for researchers and actors working to transform cities through nature. To this end, digital science and technology obviously play a key role, as seen by the following example.

THE EXAMPLE OF AN ENVIRONMENTAL DIGITAL TWIN [30]

The notion of an environmental digital twin is a particularly interesting case of using modelling to support public decision-making and action. The twin developed by WSP|BG Ingénieurs Conseils[31] as part of the WG's project illustrates the problem well.

The digital twin developed by WSP|BG Ingénieurs Conseils is a decision-making tool designed to support towns in reaching the goal of zero net artificialization (ZAN 2050). As a reminder, the **zero net artificialization policy** (ZAN) aims to reduce the artificialization of land, measured quantitatively by an increase in the artificialized surface area, and qualitatively by changes in the characteristics of natural soils. Faced with the regulation following the laws of 22 August 2021 (Climate and Resilience) and 20 July 2023, local politicians are looking for tools to help their territories move in this direction of reducing artificialization, which therefore means stemming the increase in built 'paved' surfaces around the country.

The company's work is carried out through a Cifre PhD project on urban planning, initiated by Fanny Josse in 2022[32].

The digital twin has been defined as **an avatar of a set of physical entities, based on continuous dynamic and static data**. This continuity is essential because it makes it possible to simulate, diagnose, monitor and control the behaviour of physical components throughout their lifecycle.

The research focuses on data related to soils and their artificialization, while interrelating them with a set of connected dimensions, both physical and socio-economic. The aim is to develop a simulation tool that is **easy to use, transparent** in terms of data and computing, and **capable of adapting fast** to changing regulations. The difficulties to overcome include the following:
— the numerous interpretations of calculations,
— the legal complexity between environmental law and the law on urban planning,
— the wide range of actors and decision-makers involved

The **advantages of an environmental digital twin** are numerous:

— **Integration of numerous data:** a combination of data from diverse sources (meteorological, ecological, hydraulic, etc.) is used to build a realistic vision of the complexity of urban realities, by precisely simulating the different urban planning and management solutions under the constraint of the ZAN.

— **Dynamic scenarios in real time:** the digital twin integrates real-time data to react rapidly to changes in the urban environment, for example by adjusting measurements of stormwater management to correspond to the weather forecast, or by organizing urban planning differently to correspond to new regulations.

— **Accessibility and visualization:** a platform can be used to easily access all of the statistical and dynamic data; thanks to representation tools, infographics, etc., decision-makers can see in real time the impact of an urban intervention at different time horizons.

29 Convention industrielle de formation par la recherche [industrial agreements for training through research].

30 This example is based on the presentation by Sylvain Riss and Fanny Josse, WSP / BG Ingénieurs Conseils – WG meeting on 17 June 2024.

31 WSP|BG Ingénieurs Conseils is an engineering firm working on Infrastructures, buildings, energy, industry, water and the environment. It also provides consultancy services to local authorities on urban issues, urban development, and the complexity of urban management.

32 PhD jointly overseen with the Lab'Urba laboratory, at Gustave Eiffel l'University, supervised by Bruno Barroca, and Sylvain Riss for WSP|BG Ingénieurs Conseils.

However, despite its numerous promises, the environmental digital twin faces significant challenges.

— The intrinsic complexity of the representation of territories, a system of systems, each one of which rapidly evolves: *"A territory is not an automated system that can be quickly understood and forecast, but rather a **living system constantly evolving** through the variations and developments of its physical constructions, economic and political activities, and social and cultural frameworks. Current simulation technology cannot always pick up on the complex details of materials and the dimensions of an infrastructure, nor describe complex external environmental factors."*

— Digital tools contribute to the systemic effectiveness of the actions implemented; however, much remains to be done before **urban data can be integrated and exploited to reflect** their physical, chemical, ecological, social, economic and political **potential**.

— Nature modelling initiatives call for **broad, concerted training efforts,** ranging from highly specialized levels (more researchers and informed experts to pass on their results) to more general levels. Local leaders, presidents of associations, managers of companies involved in urban operations: each needs to possess a certain competency, or at least be aware of the issues, methods and uses of nature in the city and its modelling: origin of data, conditions of usage and interpretation, etc.

The quality of dialogue between researchers and decision-makers could be greater. Along with high expectations, these sensitive but urgent challenges can be subject to bias, as related by one researcher: *"When local authorities call on us, for example, we have to tread lightly: we don't want to deliver results that turn out to be unreliable"* to decision-makers keen to get hold of reliable, simple recommendations. Progress must be made by both those producing increasingly reliable and 'adoptable' knowledge, and from the users who need to handle their reliability conditions.

3. The example of Technosols: from land to models, from models to application

Constructed Technosols are a solution aimed at solving the need for soils possessing sufficient functions to respond to a range of needs, such as in the city.

These artificial soils are produced using recycled or exogenous materials to reproduce the same functions as natural soils. Technosols respond to the objectives of the Climate and Resilience Act and the ZAN (zero net artificialization) because they are a way to remove waterproofing from urban surfaces and restore the ecological environment: suppression of asphalt or bitumen layers to replace them with permeable soils – either natural soils or Technosols. The latter can compensate for a shortage of natural soils acting as a vegetation substrate in the city. In general, they can be used to recreate fertile soils in urban environments while optimizing the use of local resources and limiting their environmental impacts.

Soil made impermeable due to urbanization loses a large part of its **ecological functions**: reduction in gas exchanges, loss of biodiversity, reduction in the capacity to retain water, and standardization of landscapes. Constructed Technosols can restore some of these functions by imitating the stratification (soil 'horizons') and physical-chemical properties of natural soils. To achieve this, materials are sorted, analysed and mixed to create horizons with the specific properties required for a particular usage, in terms of density, pH, organic matter content, etc.

These Technosols can be adapted to a range of urban uses: green areas, green roofs, parks, and urban agriculture. In all cases, their **composition and structure must be carefully modulated** in line with local pedoclimatic conditions, the materials available, and the objectives (ornamental vegetation, urban agriculture, recreational areas, etc.). For example, to construct green roofs, Technosols must be quite light, and so not too thick or dense. Materials like broken bricks can be used for draining, while organic mixes like compost and coffee grounds are added to encourage plant growth.

Due to their initial composition, or mechanisms of change that we still do not perfectly understand, Technosols can be exposed to **risks of contamination** from heavy metals or microplastics comprised in the materials used in their construction. These contaminations raise questions regarding the use of these soils for activities like urban agriculture, where health and safety standards must be strictly respected.

Soil biodiversity is another major challenge in the success of urban renaturing projects. Technosols must therefore not only support plant growth, but also the diversity of micro-organisms and animals that make up underground ecosystems. This dimension has been little studied. It can take years for the biodiversity colonization of Technosols to stabilize. Experiments have shown that the presence of earthworms, for example, can be difficult to obtain in artificial environments like green roofs. This colonization depends on the quality of the substrate created, as well as on the connectivity of the areas featuring Technosols (brown belts, green belts, etc.).

Numerous questions remain to be answered concerning the preservation of biodiversity in Technosols: *"How can it be integrated upstream and downstream? What are the ways to characterize, measure and monitor it? Is the number of species present a sufficient criterion, or should others be included? How do you integrate the desire to avoid the development of invasive species? How do you*

adapt the level of preservation of biodiversity according to objectives? For example, fertility issues and health risks are not the same for food production as for ornamental production."

Technosols are still an **emerging research area**. Most studies focus on laboratory-controlled environments, and much remains to be learned about their behaviour in the long term and in real contexts. Some research areas therefore involve extending knowledge in this direction. Another avenue involves developing good practice guides for the design, management and monitoring of Technosols, with state-of-the-art indicators to measure biodiversity, fertility, the capacity of Technosols to store and filter water, etc.

As we can see, designing and managing Technosols requires a **multidisciplinary approach** involving pedologists, ecologists, biochemists and urban planning managers.

Example: The SITERRE project[33]

Project funded by ADEME (French Agency for Ecological Transition) from 2010 to 2015
Goal: to develop methods to produce fertile soils in urban environments using recycled materials, like industrial and urban waste.
The research was based on the European Waste Catalogue to identify and select diverse materials for use in the composition of Technosols.
Of the 836 types of waste listed, 27 were preselected, of which 11 were retained (6 mineral materials and 5 organic or organo-mineral materials).

Objectives:
- develop models to predict the fertility of mixes,
- evaluate and control health risks for people and the environment,
- create a decision-making support tool,
- propose the establishment of a new production channel.

Five usage situations were identified as presenting strong opportunities for constructing fertile soils (squares and parks, support for public buildings, roadside trees, etc.). For each type of use, an optimal functionality level for the soil to be constructed was defined, involving several parameters.
75 mixes combining two or three materials were tested in different laboratory conditions and on-site. Evaluations of the innocuity of mixes and soils for humans and the environment were also undertaken.

Lastly, a **multi-criteria decision-making tool** was designed to support the production and laying of Technosols, taking into account the technical, economic and societal constraints for a given land use.
The SITERRE project demonstrated the interest of Technosols as an alternative to consuming natural resources when creating planted areas in urban environments. A publication summarizes the results and the perspectives for establishing a dedicated production channel along with its acceptability, regulatory framework, and associated communication issues.

A new project, SITERRE 2 (2022-2026)[34], extends this work, with a greater focus on **experimentation in real-life conditions, support for decision-making, and the establishment of the production channel.**

Technosols constitute a significant innovation to tackle the challenges of removing waterproofed surfaces and renaturing. Additional research is nevertheless needed to understand their long-term behaviour and their impacts on the environment and human health, in different urban contexts.

33 Source: WG speaker, and VIDAL-BEAUDET Lauren "Une méthode d'écoconstruction de sols fertiles pour la ville: le programme SITERRE", *Pour* journal, 2018/4 No. 236, p.79-86.

34 Initiator: Plante et Cité. Partners: BRGM, IFSTTAR - Gustave Eiffel University, Institut Agro - Agrocampus Ouest (EPhor), University of Lorraine - INRAE - GISFI (Laboratoire Sols et Environnement), UNEP. Funders: Ademe (AAP Graine), Pays de la Loire Region.

03 Mobilize and equip the actors of regenerative cities

The innovative knowledge and knowhow set out above contribute to answering the question of how to improve nature in the city, including relevance conditions, etc. It is also important to work on the **socio-economic demand (in the broader sense) for nature in the city**: what are the political, legal, economic and social relevance conditions that make society a suitable environment for developing nature in the city?
This question was treated in less detail than the previous one, but the working group nevertheless identified a number of avenues.

1. Understand and support the transformation of actor systems

REVISITING THE FRONTIERS OF URBAN ECOSYSTEMS

Developing nature in the city entails considerable changes in the socio-economic, environmental and political dynamics of urban spaces. It calls for major reorganizations of territorial ecosystems, which involve redefining the roles and positioning of their various actors. Local public authorities, economic actors, associations and citizens, researchers and experts must integrate new criteria in their missions and actions, and coordinate differently to tackle the totally new challenge of planning and operating the town differently. This gives rise to frictions, even contradictions, that call for adjustments. These adjustments are obviously complex, insofar as they upset established identities, rules and economic models, etc.

These challenges of reorganizing the ecosystems related to developing nature in the city are illustrated, for example, by the **PhD defended by Julie Lombard–Latune** in 2018.

J. Lombard Latune, "La compensation écologique : du principe de non-perte nette de biodiversité à son opérationnalisation. Analyse de l'action collective" [ecological compensation: from the principle of a net non-loss of biodiversity to its operationalization. Analysis of joint action][35]
This thesis analyses the dynamics of actors involved in implementing ecological compensation, through three large-scale projects for high-speed train lines. It identifies a series of mismatches between the goals (limitation of ecological impacts, and in particular 'net non-loss of biodiversity') and the way that the actors operate.

Examples:
Time mismatches: for instance, land management systems make it impossible to implement compensation measures sufficiently early. The long-term viability of these measures is also inadequate: stability of support structures , way in which monitoring and control missions are carried out, etc.
Scale mismatches: compensation sites are too small compared to impact areas.
Organizational mismatches: coherence between missions and responsibilities (a commercial company that owns a site does not have a primary goal of preserving biodiversity there), ways in which contracts are drawn up between actors, etc.
The thesis thus sheds light on the limits of implementing ecological compensation as a tool to preserve biodiversity in infrastructure projects, limits related to problems of consistency and coordination within actor systems.

35 Geography PhD thesis, defended at Paris Saclay University on 20.12.2018 under the supervision of Nathalie Frascalia Lacoste and Harold Levrel.

Other, more operational examples relate to the way in which existing ecosystems, and in particular economic channels, are taken into account in research projects aimed at developing urban nature-based solutions. The challenge: understanding them better and supporting their changes due to the different model represented by developing nature in the city, to ensure better conditions for adoption and implementation.
Two examples.

The **GreenStorm project,** winner of the European Partnership Call for Projects 2022, centres on the design and deployment of nature-based solutions for stormwater, for resilient cities that are pleasant to live in.[36] It tackles the question of implementing nature-based solutions to manage urban stormwater, and their performance and resilience in extreme climates now and in the future. The objective is to identify effective solutions, and levers to encourage their implementation at city scale and maximize the associated benefits.
Beyond the scientific and technical dimensions of the benefits and the hydraulic, thermal, chemical, etc. impacts, part of the project focuses on the acceptability of the solutions sought and the conditions for their dissemination, through five cases of European agglomerations. One of the challenges of the project is to *"foster dialogue between stakeholders and support them to develop innovative NbS that are effective, resilient and acceptable (technical departments, local residents, etc.)"*, and to *"dialogue with local authorities to achieve designs that are better adapted to local contexts"*. The project should lead to *"experimenting more collaborative approaches for implementing NbS in urban planning projects"*.

Another project worth mentioning is **SITERRE 2** (2022-2026)[37], led by Plante et Cité (see the box on SITERRE 1 in the previous section). This second stage involves developing work, "Towards eco-efficient recovery of waste and industrial or urban subproducts to develop fertile soils". The aim is to finalize a predictive tool to support decisions based on studies and modelling of material mixes. This tool is based on multicriteria analyses and case studies on pilot sites. Beyond dimensions linked to materials and environmental impacts, these analyses integrate socio-economic dimensions of cost and acceptability. In parallel, a survey was carried out of professionals in the industry to understand current soil-construction practices and developments in constructed soils.

As we can see, the issue of interacting with economic channels, and more widely, with urban ecosystems, has been clearly identified in research projects and avenues. More than simply communicating about the changes underway or results, this approach means **involving urban communities** in the changes that they will need to adjust to as the city is renatured.

CO-CREATING NATURE IN THE CITY WITH ITS INHABITANTS

The communities concerned by renaturing the city obviously include its inhabitants. Researchers and social-urban innovators have for a long time been exploring the ways in which to involve residents in urban changes. Without claiming to produce a general state of the art of practices and perspectives in the area, we can mention several areas looked at by the WG.

One participant started by mentioning that **human and social sciences (SHS)** are naturally the most closely involved in the field of citizen participation. *"How are social behaviours taken into account when implementing and managing revegetation? Improving revegetation may also mean considering users and inhabitants. Isn't there a link missing between teams of engineers in charge of all of these works and developments, and the SHS teams that should be taking part?"*, she asked following a presentation of the work of Lab Recherche Environnement, involving three engineering schools and Vinci. In response, a member of the Lab agreed, while reminding the group that since the Lab partners were not SHS specialists, social dimensions are considered to some extent, but undoubtedly required more detailed deliberation.
Work also focused on **behaviour and social representation issues** related to the development of nature in the city.
For example, a PhD on domestic gardens currently underway aims to identify practices that tend to increase garden owners' impression that they are connected with nature, which is a potential lever to foster pro-environmental behaviour among urban citizens.
To go further, the Lab plans to launch a call for expression of interest aimed at the SHS community, in order to supplement its expertise, in particular on issues of energy sufficiency.

In addition to mobilizing the social and human sciences, an important avenue for progress resides in jointly building and creating urban innovations with inhabitants. Different initiatives centre on establishing and running these approaches. In this area, one speaker recommended *"pursuing the development of **living labs**"*, with the aim to *"do research differently and get that kind of research to be recognized."*

36 Project GreenStorm, *Design and deployment of stormwater nature-based solutions (NBSSW) for resilient and livable cities (2024-2026)* - https://arceau-idf.fr/en/projects/greenstorm
14 partners in five countries (Denmark, France, Greece, Italy and Sweden), including 7 academic partners (for France: Ecole des Ponts ParisTech, Cerema, and Gustave Eiffel University), 6 local authorities (for France: Seine-Saint-Denis, Ville de Paris) and an SME.

37 https://www.plante-et-cite.fr/projet/fiche/79/siterre_ii_vers_une_filiere_eco_e

One example of citizen participation through a living lab was presented to the WG by the **Dédale association**.
Established in 2002, Dédale is an urban and social agency that works on urban planning, nature in the city, development, mobility, culture and education, and puts citizens at the heart of its projects.
Dédale's activities include project management, research and experimentation, the creation of artistic events, studies and project management assistance for local authorities. Starting out with an activist approach, including actions like *Guerrilla Gardening*, the association now takes a 'tactical urban planning' approach that puts the emphasis on progressive, experimental modifications with a view to permanent change. For example a 'Parking Day' event was following by a project with the City of Paris to test innovative usage of parking areas: 8 square metres were transformed into replanted areas or innovated shared areas, over six months.

> **Dédale** now manages the **Rosa Lab**, a 300 m² third place connected to a 600 m² community garden located in northeast Paris (19th arrondissement). This area and the surrounding neighbourhood has received the **Smart City Living Lab** EU EnoLL label, supported by the European Commission, for putting the user at the centre of a research project in collaboration with other stakeholders (local authorities, laboratories, private sector). The Living Lab is defined as 'a space for research and experimentation on sustainable, innovative cities, that places citizens, as users, at the centre of our projects'.
> The following questions are key: how is the project of interest for inhabitants? What is the geographic and socio-economic context? What type of inhabitants can (or should) be involved in the project (families, unemployed people, communities with immigrant backgrounds, students, etc.)? How?
> A new project is currently being set up: a **French Living Lab for the EU's Mission Soil** de la Commission européenne (Horizon Europe Programme), in partnership with CEREMA, the City of Paris, and the former industrial site, Le Transformateur in Saint-Nicolas-de-Redon. This new open innovation space will be a place to study and experiment citizen participation in renaturing urban land, in particular the legal, social and economic aspects.

Featuring shared experiments, participatory workshops, inclusive initiatives, etc., the co-creation of (re)natured urban areas can lay the foundations of a 'greener' city with and by inhabitants – which is a necessary condition for sustainable change. When accompanied by SHS research, these initiatives represent genuine *in vivo* laboratories of nature in the city. More widely, the place of human and social sciences can be strengthened in urban projects and in more inter-disciplinary projects in this area.

ENSURING IMPROVED SKILLS FOR THE ECOSYSTEM

For every local elected representative, every association president involved in preserving or developing urban territories, and every company manager involved in urban operations, the question arises of the level of skill required in terms of the challenges, methods and uses of nature in the city. Dialogue between researchers and decision-makers can only improve as a result.
These sensitive, urgent challenges are subject to bias as much as high expectations from decision-makers looking for reliable and (especially?) simple recommendations. For instance, urban planning agencies often opt to use tools based on excessively limited measures (e.g. the result of a temperature measured at 3pm used as an average base); *"the differences between model results and reality have created unpleasant surprises for local authorities, which have become wary."*
Another speaker observed: *"Elected representatives are very quick to pick up on popularization tools, with all the problems that they can lead to because they don't consider numerous parameters."*
A good example is a square in the city of Nantes, beside the Loire River, facing dominant winds offering all the conditions for natural urban cooling; however, because the aeraulic dimension was not taken into account in the urban planning project, the potential was totally overlooked and only thermal representations were included.

Another example is local politicians' appetite for planting trees in cities. This concrete action, which is visible to citizens and seems relatively simple, can open the door to numerous ecological and economic absurdities if the feasibility conditions are not carefully studied. One case mentioned is eight elm trees imported from the Netherlands after 15 to 20 years of growth, and replanted on a square in the South of France, at a total cost of 300,000 euros (elms + installation in pits), added to another 1.8 million euros on works to create the pits.

It is therefore essential that in addition to researchers producing new knowledge or improving what exists, the numerous users that will use such knowledge should learn how to understand it and implement it by respecting the conditions for its validity.

In this area, significant disparities exist in urban ecosystems. For local authorities, *"you shouldn't talk about the 'city', but rather about 'cities' because they're so different, in so many ways. They also have* ***highly variable levels of competency:*** *some have a great deal, with large dedicated services, while others have a lot less, either because they're smaller, or because they've invested less on these new subjects, which leads to very different adoption levels of the challenges, objectives and tools."*

Local authorities are starting to be aware of the number of skills required, as one speaker related. During the POPSU programmes and the establishment of an observatory on urban heat issues, when leaders

called on local authorities to ask them if they wanted to come and exchange on these subjects, *"some of them asked if they could come along with a researcher – although was in fact the rule of thumb"*. In some cases, local authorities possess in-house skills, but they are too 'siloed' and therefore difficult to mobilize in the right conditions.

Identifying the right communication and training formats is therefore crucial, so that public and private decision-makers can have sufficient benchmarks to ensure that their initiatives are in line with the scientific, technological and social state of the art.

One speakers thus said that, *"The question is how to put these tools in a context that makes them useable by very different stakeholders, from researchers to civil society: you need all-round dissemination because the subjects are essentially societal. The aim is to have a really systemic approach that isn't limited to 'technical' science, but includes social and human sciences."*

> Among the interesting means of adoption, is the ***serious game*** developed following the PhD by Julie Lombard Latune on **organizing the actors of ecological compensation**, mentioned above ("Repenser le design des écosystèmes Ville-Nature-Société" [rethinking the design of city-nature-society ecosystems]). The target of maintaining the ecological status of a territory involves a range of interacting stakeholders: farmers, forest rangers, mayors, associations, promoters, etc. Diverse developments are proposed, leading to evaluations of the impact on biodiversity; the stakeholders can suggest compensation measures and adjust their proposals, etc.

Another operational example: the objectives and limits identified by research can be 'translated' in the form of key indicators, which are easy for stakeholders to integrate. One speaker mentioned the **'3 – 30 – 300' rule** developed by the University of British Colombia[38]: each citizen should see three trees from their window, have 30% tree canopy in their neighbourhood, and be located at least 300 m from a high-quality green space. A study was undertaken in Barcelona on the impact on human health of the map resulting from this rule. The system could be applied in France, although more data and operational benchmarks are required.

Another more permanent tool to support actors is **Assistance à Maîtrise d'Usage** (AMU) [usage control support], mentioned by a doctoral student participant. This approach, which is used in adult training, consists in **including learners in the engineering of their future training course**.[39]
AMU acts as an approach, a method, and a professional mission, regrouping disciplines and skills from human and social sciences (sociology, social psychology, anthropology, etc.), popular education, design, architecture, spatial planning, ergonomics, coaching, etc. On the field, the support involves all stakeholders – inhabitants and professionals – so that users really play a role and can be actors of their built living environment, notably through making connections with technical experts. All of the life cycle phases of building production and all types of collective buildings are concerned.
This approach is today recognized for its contribution to the ecological transition, community dynamics, and the sustainable development of territories.[40]

Developing innovative methods to share knowledge on the challenges of nature in the city within urban ecosystems, disseminating and evaluating them: this work avenue is clearly a priority to bring together rapidly evolving knowledge and the considerable application needs of this knowledge in controlled conditions.

2. Reinvent the benchmarks and modes of public action

RETHINKING URBAN PLANNING AND DESIGN POLICIES

Urban planning and design policies are obviously directly concerned by the issues of developing nature in the city. These issues have been considered for decades, based on benchmarks that have significantly changed, the history of which has provided the subject for numerous works. An initial remark: this history largely conditions current and future trajectories, and it is therefore important to know it, understand the forces that drive it, and draw from it to plan future changes in direction, including their most technological dimensions.

The aim here is not to give an overview of this historical knowledge, but to indicate some of the key questions that currently concern these urban policies on nature in the city, and which were mentioned during the WG's work.

38 https://www.sciencedirect.com/science/article/abs/pii/S0048969723063660

39 Karine Sautereau, *La co-construction de dispositifs de formation favorisant la transition écologique au sein des organisations. Impact(s) de la maîtrise d'usage sur l'engagement des apprenants en formation* [jointly building training courses that foster the ecological transition in organizations. Impact(s) of usage control on the commitment of learners to their training], PhD thesis on education and training science supervised by Sandra Enlart - Equipe Cref-ApForD, Paris Nanterre University, Cifre thesis at Centre-Inffo.

40 See *Livre Blanc de l'AMU. Remettre l'humain au cœur du cadre de vie bâti*, financed by the Banque des Territoires, IFPEB, Kardham, Smart Use, Ville et Aménagement Durable, 2020: https://www.reciprocite.com/UPLOADS/PAGES/14/DOCS/reciprocite-756382-le-livre-blanc-de-lamu.pdf

What are the priorities?

Developing nature in the city raises complex questions that require reconciling sometimes contradictory priorities and goals.

One of the most obvious examples today results from the **policy on zero net artificialization**. The ZAN's aim is to slow down urban sprawl to preserve natural and farm land, by promoting urban densification. This involves encouraging building upwards or rehabilitating already-urbanized areas. Yet **making the city denser** to respond to a need for housing and infrastructure in cities where space is often short **can reduce the space available to create green and natural areas in the city.** The choices to be made in terms of land use policy are therefore particularly difficult. The difficulty is to come up with operational solutions that are both pertinent and acceptable, for complex equations involving a large number of parameters of different types – technical, political, economic and social, etc.

The example of wasteland, mentioned in the first part of this paper, is a good illustration of this tension since it concerns areas between the city and nature that require making a choice about how the local authority views them and what it wants to do with them, as one speaker clearly demonstrated.
Several databases map out wasteland areas, such as Cartofriches (CEREMA) and POGEIS (Fondation pour la recherche sur la Biodiversité). The greater Paris area (Ile-de-France *département*) counts 2,721 potential wastelands, and 776 in the inner suburb that includes Paris, in 728 municipalities. Their surface areas range from 100 m² to 185 hectares.
"For research, the issue is to characterize them better and make biological inventories, to decide whether to use them for ZAN-driven densification, or rather as nature areas to be preserved; in that case, they don't necessarily need to be 'renatured', even if they seem derelict, abandoned or wild, because isn't that what nature in the city is also about?"

Another well-known example is the management of water in the city (and beyond). Here once more, **water representations and usages are numerous and often a source of conflict** concerning a resource under increasing pressure. A great number of choices will need to be made between the city and other environments and, in the city, between a range of domestic, urban, and industrial uses. Developing nature in the city generates new needs that have to compete with others within a set of complex collective choices.

What kind of size?

Among the criteria to take into account when making these choices, size needs to be carefully considered. When faced with multi-dimensional questions, it is important to have general markers concerning the probable impacts of the choices to be made.

One speaker gave the example of the revegetation of the city of Paris. The municipality has established clear goals for the mandate: 100 hectares to revegetate, 170,000 trees to plant. *"The process involves prioritizing streets and neighbourhoods. There's obviously a question of proportion: de-waterproofing/revegetating 100 m² on a road with a surface area of 1,000 m² is no problem; however, if it's 900 m² on the same street, you can come up against the risk of making the subsoil fragile because of the high quantity of gypsum in a lot of the Parisian subsoil."*

What urban forms?

The whole way that the city 'takes shape' can be put into question when the priority is nature in the city: this is central to the work of urban planners and designers, who propose **urban designs that encourage nature-based solutions to different extents.**

A few examples illustrate how the configuration of a street, neighbourhood or city can be a nature-based solution in itself.

One speaker pointed out that, *"the way buildings are organized in neighbourhoods, their shape and height, etc. are the object of a great deal of research."* Referring to a summary of 109 scientific articles produced by the PUCA and the MNHN[41] on the relationships between urban forms and biodiversity, he said that that it was important to maintain connections between small parks and tree-lined streets, for example. The study also notes knowledge gaps on the impact of urban forms and biodiversity.

He added that: *"At project scale, there is also a wide innovation avenue ahead on taking soils into account at the project scale."* The standard approach of urban designers is to destroy everything at the time of the worksite and then plant new green areas. Fostering nature in the city should mean just the opposite: inserting buildings into what exists already – which assumes having good knowledge of the land before the project begins.
The speaker told us that this was the approach taken at the Courrouze commercial activity zone in Rennes by landscape architect Charles Dard, who worked on a prior land quality assessment, thus making it possible to anticipate less polluted, more fertile areas for managing rainwater and community gardens, etc.

Another speaker mentioned **two examples related to urban cooling:**

> **Intervention in a consultancy capacity on the Arenas commercial activity zone in Nice, to take over a project that the contracting authority wanted to make more ecological.**

41 Morgane Flégeau, supervised by P. Clergeau, H. Soubelet and S. Carré, *Formes urbaines et biodiversité : un état des connaissances* [urban forms and biodiversity: state of knowledge], PUCA – MNHN, 2020.

Existing bioclimatic studies recommended putting in place water-retaining slabs to maintain a cool temperature – which seemed questionable for a city that receives little rain. The discovery of older studies identified aeraulic data showing the existence of an urban wind coming down from the Mercantour national park that could potentially cool the neighbourhood.
The new site plan of the neighbourhood was therefore designed to benefit from this low-tech, natural solution.

The question of 'urban canyons': The ZAN policy can result in building upwards to make the city denser (e.g. bioclimatic local urban plan for Paris). However, if detailed studies are not carried out on the design of these streets looking at their revegetation, for example, their bioclimatic impacts can be deleterious: accumulation of heat, limited circulation of air and pollution, etc. A range of dynamics should therefore be analysed to reconcile them as best as possible: comparison of road traffic, winds, urban forms, porosity of buildings, etc. Rather than being used to restrict the wind, planted areas should be employed to guide it as effectively as possible in these urban areas.

What regulations?

When research can be used to sketch out possible solutions for developing nature in the city, to ensure that innovations see the day and stand the test of time, the key is to adapt existing regulations, which are often conceived for other types of urban organization and operations.
Although this dimension was not developed by the WG, an important area of work was identified: the need for interdisciplinary research centred on **taking a law-based angle to approach major socio-technical issues like those relating to soil, water, buildings, etc.**

Regulations involve formal legal frameworks with their own language and specific codes, but they should also open out, using research, to the need for providing more proactive support to issues like developing nature in the city.

For example, thresholds (or other conditions) resulting from scientific studies should be transcribed into urban planning and design documents, and then used to better qualify soils, plants, water, etc.
CEREMA has started to work on characterizing soils using its MUSE methodology (biophysical data). Based on this work, one speaker worked on evaluating open land scores, with different gradients that can now be qualified, on the central territory of the municipality of Saint-Germain-en-Laye[42]. The aim is to protect what exists and **integrate it into urban planning documents.** These studies also revealed a need to verify cartographic data on the field.

Another example developed by a speaker refers to a **need for flexible application of standards** when it comes to 'green' solutions, which are naturally more variable than those applying to 'grey' solutions. Faced with this variability (cf. first part), how should we respond to regulatory constraints that are rigid by definition?

> *"Every municipality and each agglomeration has its own regulations that establish certain thresholds: retention of so many mm in case of rain, maximum flow, etc. However, with the double space and time variability of pluviometry on the one side and NbS on the other (depending on initial time conditions and their spatial layout), it's complicated to guarantee 100% respect of these thresholds and standards. Complex calculations are carried out to* ***evaluate the capacity for respecting these regulations: e.g., a drop from 100% to 90% compliance. Recognition of these margins would make it easier to implement NbS."***

Regulatory tools also obviously have their limits. Bearing in mind that only **10 to 15% of green areas in cities are public, levers can be less direct on most of the urban territory.** Having said that, other means of intervention may exist, such as, for example, the possibility of creating zoning or ratings (including for a single tree). Many local authorities are nevertheless considering more action on private areas. Beyond the regulatory dimension, **information, awareness-raising and incentive actions** can help change the decisions and behaviours of urban actors. Deploying social innovation to promote political will is a lever that merits wider usage.

DEVELOPING MULTI-SCALE GOVERNANCE

The management of space and the design of urban networks based on engineering and technological rationale traditionally interconnected at the scale of the city as a governance space: creation of 'grey' infrastructures, control of urban land, local regulations applying to all neighbourhoods, etc. While coordination with the region and state levels was undoubtedly necessary, competencies could be distributed (relatively) coherently.
NbS, on the other hand, are part of much larger geographic and temporal continuities, and their diversity fits into a wide range of specific local conditions. Government frameworks need to evolve towards much better integration of the conditions in which needs and resources are managed.

42 Tutored project involving biodiversity, ecology and evolution masters students at Paris-Saclay University: Danna Araujo Arias, Antoine Vallée, Solène Quéinnec, Clément Parant.

One speaker developed the example of water management: *"It's important to interconnect the different space and time scales to make them compatible. That involves* ***effective, global, integrated water management."***
Local authorities have five jurisdictions related to water: drinking water; sanitation; urban stormwater management; management of aquatic environments and flood prevention; external fire control.
These jurisdictions tend to be shared within inter-municipal groups. This integration could mean taking a more integrated approach to the multi-functionality of water and the organization of its management. *"However,* ***this cross-cutting ambition is still rarely carried out in practice****, with different regulations depending on the jurisdiction and the silo organization of local authorities."*
Some of these jurisdictions seem to be more suitable for deploying NbS, such as stormwater management or flood risk, with associated disciplines: e.g. urban hydrology, with actor networks already in place.
The context is less favourable for other jurisdictions like drinking water and sanitation, due to the **hygiene paradigm, security issues, and the industrial and commercial nature of these services, which tends to put the accent on the financial value of water.**

Here once again, **striking a balance between the micro and macro scales** is difficult, with a need for interactions, *"between responsibility and financing levels that are both related and different (installation/maintenance, water/green spaces, etc.). There is no one good solution, beyond making greater efforts to integrate stakeholders based on the new ways of thinking, and especially citizens."*

Even beyond these governance frameworks which go from Europe to citizens, the question arises of the lack of entities to integrate in these governances: in France, as a speaker pointed out, *"****we have water bodies that are manager 'orphans';*** *so how do you act on those bodies and water tables when there's no one in charge?"*

As we can see, the state, regions and local authorities need to work closely together to guarantee the consistency of policies aimed at putting nature back into the city, maximizing the impact of their financing, and ensuring sustainable management of these green infrastructures. This multi-level governance is indispensable to ensure that the management of urban natural assets becomes a priority shared between all levels of the city.

Decompartmentalizing services and organizations

A more specific issue whose impact is however often mentioned is good coordination between urban services, which could be internal services at local authorities or para-public services.

As we have mentioned many times, the challenges raised by nature in cities are cross-cutting due to the multi-dimensionality of the needs or questions, and the multi-functionality of the resources and solutions. However, institutional organizations are necessarily segmented into domains calling on specific actors, skills, rules and means of action. To deal with the transversality of nature in the city, several avenues are possible: **totally rethink the frontiers between services or institutions, pool a number of approaches and means, strengthen cooperation between services.**

Due to the specific inertia of organizations (which can also be a sign of stability and efficiency), these avenues remain insufficiently exploited. In the absence of necessary interactions, numerous initiatives cannot be carried out successfully in good conditions, or are limited in their scope and impact.

> This question was illustrated by one speaker in her presentation on the creation of **rain zoning in the City of Paris (Plan Paris Pluie)**. She pointed out that the city *"is a gigantic organization (...). When you start talking about co-benefits, beyond purely hydrological benefits, you come up against issues involving sharing out responsibilities, funding, etc. between the domains and services concerned. For example, the green space maintenance service might wonder whether it is solely responsible for paying for the maintenance of a planted strip that will be beneficial for water management, biodiversity protection, human health and quality of life, etc. You therefore get resistance within the authority when you try to develop that type of solution."*

This question relates to the types of competency available in the different services and the way they are combined – or not – in the definition of the rules, thresholds and approaches to cross-cutting issues: *"The question of knowing how to write the rule is important – it is currently coming up again with the updating of the zoning."* And the need for cross-cutting expertise also arises: *"You need to evaluate whether it's better to have a concentration of de-waterproofed soil to allow for more infiltration, or a leaking, over-stretched pipe"* – an evaluation that is generally split between two risks, when they come under two different services.

3. Economic models: advance on the question of values of nature in the city

OPERATIONAL SHS RESEARCH MOBILIZED ON THE SUBJECT

The question of economic models for the development of nature in the city is clearly relevant today, given the affirmation of often-competing needs: **what has value in terms of nature in the city, for whom, and how do we evaluate and attach value to these natural assets?** Living close to a beautiful

park or a river with pleasantly landscaped banks, or having a view over a tree-planted square are assets that contribute to the price of urban housing. They do not however count for much in the main urban planning approaches, in particular in the face of economic pressure on land.

These questions were not central to the work of the WG, which did however underline their importance. Note that previous WG studies led to stimulating reflections and solutions regarding these issues straddling environmental and economic concerns. An interesting contribution in this area was the presentation made by Benoît Boldron, a guest speaker at the WG meeting of 23 April 2023 organized in partnership with the French Academy of Technologies on the theme of "Ville renaturée et régénérative : des concepts à la réalité, quels enjeux pour la recherche et l'innovation?" [43] [renatured, regenerative cities: from conception to reality, what are the challenges for research and innovation?]

The focus areas are assessing the financial value of natural assets, and the positive and negative impacts of human activities on ecosystems in all their dimensions (ecological, social, etc.):
— **evaluation of negative externalities,** to charge the emitters,
— **assessment of positive externalities,** to credit the contributing parties, etc.

One example is the reuse of polluted land. A great deal of wasteland is abandoned because the new owner also owns the pollution, which has to be treated before the land can be used, considering protocols for evaluating health risk. Yet it is often cheaper and simpler to artificialize new land parcels (including agricultural land) than to use polluted derelict land.

Including new, re-evaluated or redefined values in the toolbox of public action (norms, taxes, incentives, cost- and tariff-setting systems) is a challenge that in itself represents a **considerable field of technical, socio-economic and methodological research.**

Here once again, closer interconnection is needed between, on one side, the sciences of matter, life, and engineering, and on the other hand, social and human sciences, to ensure that the various contributions are combined, resulting in **shared tools for representation, regulation and incentivization,** which are currently insufficient.

We might expect that, to deal with these issues, interesting cross-cutting approaches could develop at European level within research and demonstration programmes. A better vision of this research, and obviously greater participation from French actors, would be a positive move towards progress.

THE EXAMPLE OF EVALUATING THE COSTS OF RESTORING URBAN LAND

One interesting initiative concerning the problem of measuring costs with the aim of financially evaluating nature assets in the city is the research carried out by economists on **evaluating the costs of urban land restoration.**[44]

We mentioned above the importance of functional urban land that is capable of supplying a range of ecosystem services. Restoring deteriorated land is thus a key part of the 'Zero Net' targets established at international level (SDG No. 15.3; COP 15), and European and national levels (ZAN).

Researchers point out the insufficient knowledge of land restoration, in particular urban land, and its disparate, fragmented character. They do however mention a **France Stratégie report**, published in 2019, which provides an estimation of the costs of restoring land as part of the broader question of ways to combat land artificialization. The report estimates renaturing costs starting at €33 per square metre for a single Technosol construction step, to €455 per square metre for restoration involving all steps (deconstruction, depollution, construction of a Technosol). This estimation is nevertheless **incomplete**: sources outdated or missing, methodology not described. Researchers therefore returned to the question of determining how to restore urban land and at what cost.

Ten stages of land restoration were identified. The results showed that the costs of each stage can be very different. For example, cleaning up the land and demolishing buildings are particularly expensive, whereas preliminary studies and revegetation are less costly (in €/m2).
Cost variability factors were also identified, such as potential economies of scale, and the presence of asbestos when demolishing, the level of soil pollution, etc.

The decision to break down artificialization removal operations into several stages and sub-stages meant that they could then be arranged to create pertinent technical itineraries based on the initial state of the site and the projected state. These technical itineraries were then employed to develop scenarios representing the move from a highly artificialized state to a final restored land state.

43 Benoît Boldron, university lecturer and associate researcher – Toulouse University; and head of the public habitat service at the Department of Habitat and Land Operations - Toulouse Métropole / Ville de Toulouse, *Planification urbaine : quelle valeur environnementale pour une ville contributrice?* [urban planning: what is the environmental value for contributing cities]? Mr Boldron took the example of 'one cypress tree, six prices', showing the potential price differences for one tree depending on the context and the usage. He suggested innovative land taxation methods that take into account the positive or negative environmental contributions of urban projects on the existing situation. https://www.anrt.asso.fr/sites/default/files/2024-start/presentation_b._boldron.pdf

44 Mathilde Salin with other researchers from CIRED. See the publication: Salin, M., Claron, C., Nguyen–Rabot, E., Mondolfo, N., Levrel, H. (2024). "Les coûts de la restauration des sols urbains." *CIRED Working Papers No. 2024-96-FR.*

The total costs of restoration ranged from €25 to €465 per square metre (for non-polluted artificialized land), and up to €1,550 per square metre in highly polluted cases requiring excavation and disposal of toxic waste.

To conclude, an estimation of these restoration costs:

— **emphasizes the importance of land:** restoring land is costly, which illustrates the importance of avoiding initial deterioration;

— **measures the ecological debts** associated with land deterioration, potentially leading to funding or compensations;

— **contributes to an evaluation of investment needs** to reach zero net artificialization (ZAN) targets.

04 Example of a key cross-cutting question: how should nature in the city be maintained?

It is well known that the initial production of an object is often valued more than its upkeep over time. This is true for a building, where the initial architecture or innovative construction eclipses the banality of ordinary maintenance, and also applies to less material realities, like winning power versus exercising power. Yet for the users of this object, the **quality of its maintenance** is particularly valuable – think of broken lifts in underprivileged city areas.

Regarding nature in the city, this question is particularly crucial, as the group identified. It also shows how scientific, technical and social questions are interlinked, and yet these dimensions are often treated separately for analysis reasons, as seen the previous parts. Assuming an increased presence of nature in the city, **what are the conditions for its survival, sustainable integration, and development?** This question raises several sub-questions, of which we focus on four to illustrate their scope: political and philosophical issues; scientific and technical issues; economic issues; and socio-organizational issues.

To make it clear, the vocation of research and innovation is to tackle these issues together, despite a clear 'scientific and technical' dimension: this in fact concerns a subset of research (sciences and technologies of matter and the universe, life science, and engineering science).

1. Philosophical, cultural and political questions: should we nurture nature or let nature be?

The first fundamental question is: does developing nature in the city mean it should be nurtured or left alone? Two different cultural and political approaches are involved here.

The first approach can be qualified as **'green engineering'**, which involves active human intervention to integrate nature into the city. Developments are designed and planned to ensure that plants flourish in an unfavourable artificialized environment. This leads to the development of solutions such as revegetation, renaturing, rainwater management, etc. with the aim of responding to precise human needs: reducing heat islands, managing risks, limiting pollution, etc.
The aim here is to organize and control the development of nature to optimize its benefits for inhabitants. Specific plants are chosen for their resistance and their capacity to purify the air or limit the impacts of climate change in an urban environment. This approach is based on the idea that nature needs to be controlled and oriented to function adequately over time. This outlook underlies numerous research questions and innovation avenues presented at WG meetings.

The second approach is based on the principle that making room for nature in the city means allowing it to express its own cycles and means of organization. The main objective is therefore **to minimize human intervention and the mark left** on the city's territory to allow ecosystems to spontaneously replenish. This can for example involve maintaining or creating urban wasteland or wild gardens in which local plants and biodiversity establish themselves with no strict planning, following their own dynamics.
This vision puts the emphasis on the autonomy and resilience of natural environments, and their capacity to regenerate and adapt, even in highly anthropized environments.

One speaker explained this point of view as follows: *"We need to stop applying an exclusively 'engineered' vision of how cities work, and take an ecological approach: for ecologists,* ***not managing is a way of managing.*** *Not intervening can be better than the 'manageritis'* [45] *we've got used to. This means that we should* ***move from an attitude of developing nature in the city to the idea of developing the city starting with nature*** *(continuity of brown, green and blue belts). And more widely, move towards emerging approaches that advocate for* ***more balanced cohabitation between humans and non-humans****, in both space and time."*

The chairman of the WG also talked of the *"tension between the need to intervene in the management of nature reintroduced or recreated in the city, and the desire not to intervene (or not too much) to allow it to develop. Is there a happy medium between the two?"*

The concern of combining the best of our technological expertise and opening up to new challenges and ways of working emerges as a legitimate goal given the current state of the planet and knowledge. The objective would then be **to maximize the benefits of nature while respecting its own dynamics,** which involves reducing the human grip on nature in the city.
In France, as one speaker pointed out, *"we have a bad case of 'manageritis', probably because of our strong engineering culture: we feel we have to do something. I've seen a lot of wasteland projects in which the plan was to install decking, cut branches, etc., whereas sometimes you just need to let things be and do nothing. (...) [These areas] don't necessarily need to be 'renatured', even if they seem abandoned and wild, because isn't that what nature in the city is about too?"*

Another speaker pointed out that, beyond the direct needs of urban citizens, greater interests are at stake in this rebalancing of approaches: *"We mustn't forget the importance of the strictly ecological dimension related to biodiversity, etc. When we talk about NbS, we tend to only look at the subject of water management, for example, in terms of the services it will provide: infiltration, evapotranspiration, etc. But we should also think about* ***the objective of renaturing in itself, and maintaining biodiversity*** *– which has a meaning in itself, and which will in any case condition the rest. Will the vegetation we've planted survive? How are we going to maintain and develop it, and limit or manage invasive species, etc.?"*

This reorientation of the approach opens up two other work avenues:

— human intervention (scientific, innovative etc.) that is more focused on the rules of allocating space and its uses;

— and of course, the ways of making choices between nature and society in the city; in other words, *"the question of knowing who makes the decisions, the collective choices, following which procedures, etc."*

To conclude, good maintenance of nature in the city calls for **'letting it be more', while intervening to 'nurture' it when it appears necessary**. On this latter point, one speaker reminded the meeting that in artificialized environments, nature often needs a helping hand to stay alive. For example, *"Many people think that soil biodiversity establishes itself in urban environments. Although it does sometimes, other situations are more complex. For example, you won't find many earthworms on roofs. What's more, it can take a long time for biodiversity to stabilize, sometimes four or five years, with significant fluctuations before reaching a stable balance."*

2. Scientific and technical questions: what is the future of nature in the city?

Parts I to III identified numerous research and innovation avenues related to developing nature in the city. Below we look at two of them, concerning more specifically the issue of maintaining this nature in the city.

AGEING OF TECHNOSOLS

As we have already mentioned, the design and different uses of Technosols constitute a promising area for research and experimentation as a nature-based solution in urban environments.
The question of how these Technosols will evolve over time is however one of the questions for which we still have few answers, and even raises a number of concerns that will represent new challenges.
We know that soil and vegetation lose some of their functions as they age. However, we are a long way from knowing the **scope and entire impacts of this ageing** – in particular concerning Technosols; similarly, we do not know much about **how biodiversity develops, or does not develop, in them over**

45 The notion of manageritis is a pejorative term designating the tendency of some nature managers to over-intervene in the environment in order to conserve it or to maintain species and habitats.

time, in the absence of human intervention. Yet this knowledge is vital to determine the type of maintenance, even minimal, required to ensure that nature develops successfully in the city.
One speaker for example noted: *"We observed that a Technosol that was about ten years old had progressively been contaminated by heavy metals, even though they weren't present in the atmosphere. After ten years, the quantity measured in the Technosol (almost 100 mg/kg of lead) was nevertheless close to the maximum established threshold. We also need to look closely at contamination by emerging pollutants like microplastics. Their presence in waste means that they can sometimes be found in Technosols."*

DEVELOPMENT OF INVASIVE SPECIES

The proliferation of invasive insects and micro-organisms has become a nuisance in both cities and rural areas. The causes of this phenomenon are more or less clear: the importation of substrates and exotic plants carrying these species with the aim of establishing vegetation that will resist future impacts of climate change, global temperature rises conducive to the survival and development of these species, etc. In addition, some urban forms encourage the installation and development of problematic species (like the tiger mosquito). Other species that are problematic for health or biodiversity maintenance reasons include the electric ant detected in Toulon and the jumping worm found in the South of France.

The maintenance of nature in the city calls for different research studies to qualify the realities observed and propose potential solutions.

One speaker thus suggested **clearly identifying which species will really create problems in cities and those that can settle into an urban environment without perturbing it.** *"The MNHN carried out a study on the rose-ringed parakeet which showed that it would not lead to a decline in local bird species. Another example is the buddleia (butterfly bush), which establishes itself in places that other species don't go. This therefore calls for two types of study:*

- *on avoiding upstream proliferation, which can, for example, mean encouraging local species;*
- *and on the choice of management methods for different species, based on any problems they might pose (or not)."*

Another speaker, referring to the work of François Chiron (AgroParisTech), pointed out that *"**so-called invasive species can sometimes be a problem of perception.** In this area too, for species that don't really pose a health or biodiversity problem, non-management can be preferable to management."*

Once again, the balance to be struck between adapting ecosystems to new species that are adapted to climate change and limiting invasive nuisances is central to the issues involved in maintaining nature in the city, calling for more comprehensive knowledge of species and situations. Studies are already underway, for example, as mentioned by one participant, as part of the PEPR Solu-BioD programme, with in particular a network of Living Labs to share knowledge, experiment and promote nature-based solutions for biodiversity in the city.

3. Economic questions: what are the overall costs and accounting systems?

In terms of maintaining nature in the city, it may seem more economical to let nature be and thus avoid having to pay the cost of upkeeping green spaces: gardeners, products, etc. Since budgets are often tight, one speaker pointed out the benefits of *"having the most autonomous fauna and flora possible: the aim is having to do the least possible maintenance to ensure that developing nature in the city to the right level is financially feasible."*

However, it is rapidly obvious that the reality is more complicated, in particular due to **a lack of sufficiently detailed knowledge of the overall costs,** both concerning current situations and other types of maintenance – for which diverse scenarios can be envisaged, ranging from leaving things alone to more or less sophisticated nature-based solutions.
Recent and current studies have made progress on these questions. For instance, the 'economic evaluation' part of the Life ARTISAN project, which aims to establish a framework for deploying nature-based solutions to adapt to climate change (NBaS).[46] This was a dissertation produced by Auriane Bahuau, summarizing the existing and employable methods for an economic comparison of NBaS with grey solutions.[47]

While the *"cost of maintaining green spaces by municipalities is estimated at 1 to 4 euros / year per m²"* according to one speaker, numerous other elements are not financially estimated. *"When you collect dead leaves from the roadside, what do you do with them? Do you consider them as ecological material, even though they're probably polluted by the soil and air? This subject of maintenance balance sheets is not dealt with very well",* noted the WG's scientific advisor.

Another blind spot in the evaluation of the maintenance or non-maintenance costs of nature in the city: *"The way that inhabitants take part in managing living things, the soil, etc. in the city. We could potentially assess the economic value of this management by inhabitants",* suggested one speaker.

46 https://www.ofb.gouv.fr/le-projet-life-integre-artisan

47 https://www.ofb.gouv.fr/le-projet-life-integre-artisan/documentation-life-artisan/evaluation-economique-des-solutions

Lastly, even if we make progress on the capacity to economically assess a particular ecological or social cost, we still need to **align all of the skills and tools to consider these new data, and to generalize the dissemination and usage of new standards and accounting systems.**

Concerning the NbS involved in stormwater management, one speaker stipulated: *"At the start, we probably didn't have all the tools required for this maintenance, in particular the financial tools. But today, we know how to calculate the amortization of these nature-based infrastructures in the long term, and their provision, etc. Now we need to mobilize this knowledge and establish ecological accounting, etc. And we need to enhance the capacity to think about the entire lifecycle of these infrastructures, including culturally, beyond the initial investment."*

4. Social questions: what collective competencies, what new systems of actors, what regulations?

Maintenance issues involve much more diverse stakeholders than those involved in the initial production (including the users themselves), with higher collaboration stakes: who pays, who is responsible, and who does what type of maintenance, also bearing in mind that the benefits are multifunctional? These subjects are a source of controversy and major reorganizations between services (e.g. garden maintenance/ water and sanitation), and between categories of actors, and ultimately even the organization of new actor systems.

This subject was also covered in part III, although it was not specifically explored by the WG. Let us here simply put the accent on the **transformation of the local social system** which assumes effective maintenance of nature in the city.

Organizing this maintenance requires **mobilizing a diverse range of competencies**. One speaker warned: *"There is definitely a notion of working in a circular way in urban developments with the idea that they can self-generate … but we need to be careful to avoid giving the (counter-productive) impression that nature can manage itself. We're talking about spaces with a lot of contradictory demands, and the human hand is inevitably involved, at least in terms of political vision, translated on the field by teams, agents, urban planners, and landscape architects, who at some point are going to think about the conditions in which nature in the city, including plants and landscapes, will really be able to stand the test of time."*

The WG's scientific advisor underlined: *"The question of maintenance doesn't just involve those who design and set up NbS, and it can be a real weak spot. For a green roof, for example, you need to involve urban services, inhabitants, and explain and train – and we don't yet really know how to get the message across, apart from occasional investments in installations."*

Another example of the reorganization of social interactions around the development of nature in the city is the tensions between services within local authorities, already mentioned, which are particularly high when it comes to maintenance issues. As one speaker put it, **the fact that these solutions produce co-benefits raises problems of dividing responsibilities, funding, etc.** between the domains and services concerned. *"For example, a green space maintenance service might consider that the cost of maintaining a planted strip that will be beneficial for managing water and protecting biodiversity, human health and quality of life should be jointly financed by three or four other services."*

These different examples illustrate the fact that nature-based solutions can be qualified as **'relational infrastructures'** according to a concept proposed by one speaker. Referring to the work of Jewett & Kling[48], he pointed out that all types of infrastructure, whether green or grey, exist thanks to a web of relations: legal framework, governance, organized practices, etc. Like any infrastructure, NbS require maintenance to ensure their sustainability. Yet, he pointed out, we generally pay insufficient attention to this activity. When competencies are not directly available at local authorities, it can be useful to develop partnerships to ensure this maintenance, for example with farmers, landscape architects, environmental actors, or simply infrastructure users.
In general, he continued, ***"the question of knowing whether an infrastructure works or not is linked more to the political context (in the broader sense) than to its inherent properties."*** And it is preferable to opt for adaptative management, which will not compromise future choices.

According to this speaker, it also involves *"taking seriously the question of **social practices** imbedded in the infrastructure"*. For example, when a green infrastructure replaces a grey one, it is important to identify which formal and informal practices were involved in the previous infrastructure. A dyke, for instance, can also be employed for fishing and bathing, and getting rid of it might be a source of conflict with local inhabitants. Setting up new solutions can lead to new, unexpected practices that will ultimately need to be handled.

48 Jewett, T. & Kling, R. (1991) – "The Dynamics of Computerization. In a Social Science Research Team: A Case Study of Infrastructure. Strategies, and Skills" - *Social Sci. Computer Rev.,* 9, 246-275.

Conclusion

Parts I, II and III put the accent on the numerous areas of work related to the specific requirements for knowledge and innovation concerning the development of nature in the city, connected to a **need for more extensive knowledge of the diverse components of nature in the city, in particular due to their variability in space and time**. The insights put forward in part IV on the question of maintenance illustrate **the importance of taking a systemic approach to understand and act on the conditions for developing this urban nature**. These conditions must be considered in a coordinated manner involving a range of stakeholders, disciplines, and levels of temporal action and action on the field.

Beyond the questions of detail that condition the viability and overall 'performance' of nature in the city, another question underlies the work of the group: does this search for the genuine integration of nature in the city not lead us towards a new model or a new philosophical, social, political and economic project – a key condition to ensure its effectiveness as a solution for adapting to climate change?

In any case, research should also reflect on this question, which invites it to take seriously the complexity of the connections between the city and nature – including by questioning its own role as a means of knowledge and interpretation of reality. In other words, does research not also have a vocation to propose a **different insight into the reality of the respective needs of the various human and non-human occupiers of our earthly ecosystem?** And is it not also this insight that contributes to making nature in the city a demonstrator of ecological transition?

We leave the last words to a member of the WG:

"We can't just put in some plants and think our work is done. Nature's already in the city. We need to look at what's there, what people do with it, how we can improve it, and evaluate it over the long term – the past and the future."

Appendix A
Meetings and speakers

Several speakers were also WG members and/or participated in the work in addition to making a presentation at one of the meetings.

Meeting 1, 27 February 2024 – Introduction and framework

Charlotte Roux, research officer - Mines Paris-PSL / lab recherche environnement (ParisTech - Vinci)

Considering planetary limits at the scale of the renatured city
Patrick Stella, university lecturer - AgroParisTech

Maxime Trocmé, director of R&D deployment - Vinci (lab recherche environnement (ParisTech - Vinci)

Nature in the city: concepts, challenges and R&I questions
Marc Barra, ecologist - Agence régionale de la biodiversité en Île-de-France / Institut Paris Région

Nature in the city: research & innovation concepts, issues and questions

Meeting 2, 19 March 2024 – Air and climate in the city

Marjorie Musy, director of research - CEREMA

Climate impacts of urban vegetation: state of knowledge and current studies, issues for future research
Stéphanie Vallerent, deputy director - Climat et Territoire - ACTIERRA

Lucille Alonso, project manager - ACTIERRA

Urban cooling: innovative solutions and avenues for research
Karine Sartelet, director of research - CEREA - Ecole des Ponts ParisTech

Impact of vegetation on air quality
Anthony Danneyrolle, director of the hydraulic environment ecodesign department - ARTELIA

Bioclimatics and air quality: operational issues and scientific challenges

Meeting 3, 23 April 2024 – Water in the city

Pierre-Antoine Versini, director of research in hydrology - Ecole des Ponts ParisTech

Nature in the city to manage stormwater: research perspectives through urban scales
Jérémie Sage, urban hydrology researcher - CEREMA

Renaturing the rainwater cycle in cities and the GreenStorm project (AAP DUT 2022)
Laure Fass, energy systems engineer, research officer in charge of monitoring the Parispluie plan - Ville de Paris

The Parispluie plan. Presentation of Parisian rain zoning, a tool for a sustainable city
Christian Piel, geographer, urban planner, hydrologist - founding director of Urban Water

From landscape to rain garden: managing, controlling and reusing water in urban environments
Antoine Brochet, postdoctoral researcher (geography and political science) - Institut des Géosciences de l'Environnement (CNRS - Grenoble)

Jurisdictions, levers and limits of territorial public action to integrate NbS in the water domain

Meeting 4, 17 June 2024 – Earth: urban soils

Christophe Schwartz, professor of urban pedology, INRAE- Lorraine University

Urban soils: uncharted land?
Sophie Joimel, university lecturer - AgroParisTech

The construction of fertile soils and the need to remove impermeabilization from urban land to revegetate cities
Robin Dagois, agronomics, urban soil and plant behaviour task officer - Plante et Cité

Renaturing the city with Technosols: impact on soil biodiversity
Lukas Madl, doctoral student in urban planning and design, Gustave Eiffel University / AREP

Renaturing, refunctionalization, restoration: choosing the right terminology for a recent field
Cécile Brazilier, European Project Manager - DEDALE

The Terroir Urbain project
Mathilde Salin, doctoral student - CIRED / Banque de France

The costs of urban soil restoration
Sylvain Riss, director of group, digital & BIM - WSP|BG Ingénieurs Conseils

Fanny Josse, architect and doctoral student - Gustave Eiffel University / WSP|BG Ingénieurs Conseils

The environmental digital twin, a decision-making tool to meet the ZAN 2050 target?
Caroline Gutleben, director - Plante et Cité

The evolving challenges of nature in the city and perspectives for 'nature cities'

Appendix B

Members of the working group

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Richard AUDOIRE, DASSAULT SYSTEMES
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