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Assessing impacts of Land Use and Climate Change on Ecosystem Services, in Île de France, using InVEST models.

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A mia sorella,

che amo come il mondo.

"siete voi di città che la chiamate natura*. È così astratta nella vostra testa che è astratto pure il nome. Noi qui diciamo bosco, pascolo, torrente, roccia, cose che uno può indicare con il dito. Cose che si possono usare. Se non si possono usare, un nome non glielo diamo perché non serve a niente."*

Paolo Cognetti, Le otto montagne

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ABSTRACT

Models simulating the impact of land-use policies on Ecosystem Services (ES) are valuable tools to inform decision-makers. They indeed help understanding how the goods and benefits that ecosystems provide to humans may vary due to public policies. The present study was conducted to assess the impacts of Climate and Land Use Change on Ecosystem Services, to deepen the understanding of their respective relevance and joint effects and to investigate whether currently available and widely used InVEST's models are capable of grasping not only the implications of Land Use Change (LUC), but also the ones of Climate Change (CC) on Ecosystem Services. The models used were created by InVEST, a suite of spatially explicit models that enables decision makers to assess quantified trade-offs associated with alternative management choices. An historical overview of the evolution of ecosystem services was delineated and future projections were included. The study area is Île de France and the time interval that was considered spans from 1982 to 2050. For the past years, historical data on climate and land use were used, while, to have a reliable projection of ecosystem services in 2050, various scenarios were taken into consideration, using different levels of intensity, for both urbanisation and climate indicators. The study shows how future scenarios of climate and urbanisation interact and impact various ecosystem services (Seasonal Water Yield, Nutrient Delivery Ratio, Urban Cooling, Urban Flood Risk Mitigation). The research shows for each ES studied, whether the impact of CC is greater or lesser that the one of LUC, and how significant is the variation of ES between now and the future scenarios. In a broader sense, climate change and urbanisation cannot be ignored as their joint impact can substantially change life standards of inhabitants. It is therefore imperative to rightly inform policymakers on the implications of Climate Change and Land Use Change, in order to take appropriate action while also increasing the focus on bettering the technology used for such evaluations.

ABBREVIATIONS

CC	Climate Change
EEA	European Environment Agency
EC	European Commission
ES	Ecosystem Service
IDEFESE	Île-de-France évaluation des services écosystémiques
INSEE	Institut national de la statistique et des études économiques
InVEST	Integrated Valuation of Ecosystem Services Trade-offs
IPCC	Intergovernmental Panel on Climate Change
LU	Land Use
LUC	Land Use Change
LULC	Land Use Land Cover
MA	Millennium Ecosystem Assessment
NDR	Nutrient Delivery Ratio
SLUM	Simple Land Use change Model
SWY	Seasonal Water Yield
UC	Urban Cooling
UFRM	Urban Flood Risk Mitigation

INTRODUCTION

Framework of the research

The most imperative and pressing issue that modern society is facing, is to understand how climate change will impact people's lives, what is possible to do to prevent extreme scenarios, and how can cities and countries prepare to be resilient to extreme events (IPCC, 2023). It is well known in the scientific community and outside, that Climate Change has already affected many people's lives and will do so even more in the near future. Overall the areas afflicted the most by extreme events due to climate change are the coastal areas and the global south, that see a rise respectively in sea levels and in droughts, heatwaves and floods (Chen *et al.*, 2015), however no area can be consider spared by it, as changes in climate, such as weather patterns, rises in average temperatures, precipitation frequency and intensity have already been observed worldwide (Alamgir *et al.*, 2014; Lu *et al.*, 2018).

On the other hand, it is expected that by 2100 85% of global population will live in cities which implies that such areas will increase in size, when already existing, and that new urban areas will be develop at a fast rate, with Africa expected to be the fastest urbanising region. Meanwhile, urbanisation in Europe is expected to increase to 83.7% by 2050 with France having one of the largest build-up areas in the EU, with more than 5 million ha in 2015 (European Commission, 2020 [23]).

It's therefore evident why urban areas represent a focal point in modern studies on sustainable development and climate change as they are responsible for the majority of GHG emissions (70%) (European Commission, 2020) and for their intrinsic fragility and vulnerability to climate change: not only surface impermeabilization put many urban areas at great hydrogeological risk (Johnson *et al.*, 2021; Hibbs *et al.*, 2012) and the decrease of green areas reduces air cooling effects and carbon storage, but also, since cities have high levels of resource consumption (energy, food, water, etc.), and low levels of resource production, providing energy, water and food security puts great environmental stress on the surrounding areas and their ecosystems (Elmqvist *et al.*, 2021; EC 2020; Yuan *et al.*, 2019).

Through this lens, it's clear to see how important it is to focus current studies on how future cities will look like, what strains they will be subject to and what are the best solutions to embrace at the same time urban development, inhabitants' well-being and environmental sustainability.

Models are a valuable tool to understand and represent complex dynamics in this kind of systems, and they are extremely effective to obtain projections of the impacts that alternative future scenarios might have (Bullock and Ding, 2018) They are therefore widely used to study climate change and its effects both at a global and a local scale. Models are a way to represent reality or future scenarios in a simplified way, that can focus on a selected number of factors that are particularly relevant to the public they are intended to. In the case studied, models are used to give sufficient and sound information on the impacts of climate change and land use change, to a public composed primarily of decision-makers, and stakeholders (citizens, local organizations, NGOs etc.), which are generally not environmental experts, but that are nevertheless in need of a clear scientific representation of the consequences that their actions might cause on the environment.

A way to directly link the impacts of CC and LULC change to the environment, so that the consequences result tangible and practical to people that are not specialist in the sector, is to use the ecosystem services as a mirror for the more general environmental impacts, knowing that what is happening is a simplification of the observed situation, but at the same time, a representative one, when the main focus is on the interaction between humans and the environment.

Indeed, the use of Ecosystem Service modelling can change the way ecosystems are considered in policy making (Arcidiacono, 2015) since having a spatial representation of the impacts of certain resource management choices on ES can help evaluate the actual effects of a given land management project on the environment.

In this context, a useful tool is represented by the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) developed by the Natural Capital Project, thanks to its relatively simple models, its user-friendly interface and low data required. (Benra *et al.*, 2021).

For these reasons, InVEST is one of the most used tools for modelling Ecosystem Services (Posner *et al.*, 2016; Arcidiacono 2015; Salata *et al.*, 2017) and it has been used in over 185 countries worldwide [1]. InVEST can be used in the evaluation of impacts of investments in natural infrastructures, (Sharp *et al.*, 2018; Ruckelshaus, *et al.*, 2015; Grêt-Regamey, *et al.*, 2017), and in the management of natural resources (Cong *et al.*, 2020; Mandle *et al.*, 2017; Yang *et al.*, 2018) by including natural capital in the decision making process and by modelling the link between nature and people through Ecosystem Services (Díaz S. *et al.* 2018, Arcidiacono 2015).

InVEST software is free, modular and open source (Hamel *et al.* 2021), it has 25 models (as of now) that evaluate ES's biophysical processes and/or its monetary value (Arcidiacono 2015).

InVEST's models are based on simplifications of well-known relationships of the natural ecosystems. Since it is geospatially explicit, both the input data, and the results consist of gridded maps of the geographic area of study, tables, and shapefiles (Yang *et al.*, 2019; Arcidiacono 2015; Keller et al, 2015) that can help visualize and explore the possible outcomes of alternative management and climate scenarios and it can help evaluate trade-offs among Ecosystem Services (Sharp *et al.*, 2020; Hamel *et al.*, 2021).

Literature review

Since InVEST was made available, it has been greatly used by researchers to study impacts of LULC change all over the world, mainly focusing on the regional and at local scale (Arkema *et al.*, 2021; Caro *et al.*, 2020; Sánchez-Canales *et al.*, 2012) and sometimes national scale (Redhead *et al.*, 2016; Mandle *et al.*, 2017). For the low data requirements of its models, it has been widely used in rural areas (Daneshi, 2021; Echeverri *et al.*, 2022; Kantharajan *et al.*, 2022; Nel *et al.*, 2022) and in data scarce regions or developing countries, where there might be a lack of open-source data on land use and on climate (Arkema *et al.*, 2021; Dampha, 2021; Hamel *et al.*, 2021). At the same time, for the presence of models designed for urban areas (Urban Cooling) or with urban citizens' well-being in mind (Recreational), researchers have been using InVEST to study ES in urban areas (Guerry *et al.*, 2022). More than 60 studies where reviewed, and it was found that their focus spans from obtaining a representation of ES status (Caro *et al.*, 2020; Kantharajan *et al.*, 2022) to showing a historical evolution of the ES (Choi *et al.*, 2018; Wang Yunfei *et al.*, 2022), to comparing different management scenarios or scenarios of LULC change (Caro *et al.*, 2020; Guerry *et al.*, 2022) to predicting or evaluating impacts of LULC change (Dampha, 2021; Leh *et al.*, 2013), to evaluating trade-offs between ES (Guerry *et al.*, 2012; Nelson *et al.*, 2010; Goldstein *et al.* 2012) and InVEST performance (Yang *et al.*, 2019;), and finally to comparing InVEST results to other models (Bagstad, *et al.*, 2018; Caro *et al.*, 2020; Vigerstol *et al.*, 2011; Cong *et al.*, 2020; Wu, Yifan *et al.*, 2021).

The majority of articles analysed showed a focus on one or two ES (Arkema *et al.*, 2021; Benra *et al.*, 2021; Caro *et al.*, 2020; Choi *et al.*, 2018; Dampha, 2021; Echeverri *et al.*, 2022; Kantharajan *et al.*, 2022; Li et a., 2022; Manley *et al.*, 2022; Nel *et al.*, 2022; Salata *et al.*, 2017; Sánchez-Canales *et al.*, 2012; Clerici *et al.*, 2019; Wu, Yifan *et al.*, 2021), while fewer articles analysed three or more than three Ecosystem Services at the same time (Hoyer *et al.*, 2014; Cong *et al.*, 2020; Hamel *et al.*, 2021; Keller *et al.*, 2015; Leh *et al.*, 2013; Mandle *et al.*, 2017; Nelson and Daily, 2010). As reported by Nelson and Daily (2010), evaluating more ecosystem service models at the same time is very important as it helps to show trade-offs between economic development and ES to policy-makers.

Climate Change impacts are not as often included in the analysis (Daneshi, 2021) and only some papers compared the effects of LULC and CC on ES. One study (Bai *et al.*, 2019) is particularly interesting, since it gives the definition of two indexes (Relative Importance Index and Combined Effect Index) which were used to explore the relationship between CC and LULC. The paper states that depending on the model considered the relevance of CC or LULC changes: for example, in the area analysed (Kentucky, USA) CC has a greater impact on water retention than LULC while LULC is more impactful on nutrients export and sediment retention. Despite the useful definition of the two indexes, the paper doesn't use future climate indicators when considering CC impacts, but rather it compares past data with present data. Other researchers, on the other hand, included future projection of climate change, to study the provision of Ecosystem Services (Mandle *et al.*, 2017; Manley *et al.*, 2022; Sannigrahi *et al.*, 2020; Wang *et al.*, 2023) and others (Clerici *et al.*, 2019; Guo *et al.*, 2021, Hoyer *et al.*, 2014) used future projections of CC and urbanisation and compared their impacts. Overall the results showed that climate change had greater effect on water provision (Water Yield model) than LULC change in the Colombian Andes, in Jiangsu Province, China, and in the Tualatin and Yamhill basins (Oregon, USA), while Hoyer *et al.*, (2014) also found that in Oregon, nutrients exports are more sensitive to LULC change. Mandle (2017) highlights how even with no alteration of current vegetation and land use status, climate change can negatively affect water resources and increase flood risk in Myanmar.

Of the reviewed papers, only one paper analysed the Île de France region (IDF, France) (Hamel *et al.*, 2021) but didn't elaborate on future climate change inputs.

Undoubtedly, including climate change in the assessment of ES is challenging, but as Runting *et al.*, (2017) says, it would be misleading to ignore it and could lead to inefficient management of resources. Furthermore, assessing the relative and cumulative impact of CC and LULC is essential for a thorough understanding of how ecosystem service's provision changes.

The present work represents a novelty in the research field since it studies four Ecosystem Services in the IDF region, with a time span that goes from 1982 to 2050. In addition, it includes CC impacts in the assessment of ES, following (Mandle, 2016, Runting *et al.*, 2017) guidelines, and not just LULC impacts. It attempts, following directions given by Bai *et al.*, (2019) to understand the relationship between LULC and CC relative and combined effects, and finally, it gives a qualitative assessment on how different urbanisation projections and different climate projections will impact ES.

Objectives of this work

The following work has the object to investigate whether InVEST models are sufficiently suited to seize the complex relationship that exists between Land Use and Climate and to evaluate their interactions and impacts on some Ecosystem Services (ES), in particular Seasonal Water Yield, Nutrient Delivery Ratio, Urban Cooling , Urban Flood Risk Mitigation.

The first objective of the research is to delineate how the quality of some ecosystem services received by the population of the Île de France region, evolved throughout time, focusing on the period that goes from 1982 to nowadays, and furthermore to highlight, by considering a few different scenarios, what the future trends of these ecosystem services will be, taking into account a range of possible outcomes. More specifically, various possible urbanization solutions for the predicted population growth will be used, along with 3 climate scenarios for the year 2050 (RCP2.6, RCP4.5, RCP8.5)

Secondly, the study will focus on the impacts of Climate Change (CC) and Land Use Change (LUC), by using a methodology available in literature (Bai *et al.,* 2019) that highlights the relative importance of the two factors considered, and their combined effect.

The obtained results will be analysed and compared to the results expected, and finally, conclusions will be drawn on the ability of InVEST's models to consider as drivers of change in Ecosystem Services' provision not only land use, but also future climate conditions and more generally climate change impacts.

This study can be seen as a continuation and ampliation of the work done by Tardieu *et al.* (2020)

THEORETICAL NOTIONS: definitions and models

Definitions and relevant concepts

Before diving into the subject of this work, some definitions are needed with the aim of offering a deeper understanding of the topic and an overview of the most relevant concepts.

Natural Capital

Natural Capital is a term used to broaden the idea of manufactured or financial capital to also include goods and services that are provided by nature, the environment, or a specific ecosystem, and it is defined by the Millennium Assessment (MA 2005) as "the limited stocks of physical, biological and natural resources found on the Earth." (R. de Groot, 2011, E.J. Dominati, 2010). This concept has become prominent since the publication of the Millennium Assessment as the relevance of environmental systems in the overall well-being and prosperity of a country or geographical area was more and more recognized. According to the European Environment Agency (EEA), "Natural capital is the most fundamental of the forms of capital since it provides the basic conditions for human existence, delivering food, clean water and air, and essential resources. It sets the ecological limits for our socio-economic systems, which require continuous flows of material inputs and ecosystem service" (SOER, 2015). The complexity of natural system and the irreversibility of some environmental changes, often translate into mismanagement of natural capital, since decision-makers are not rightly informed on the impacts and the trade-offs of some economic choices. Natural capital can be subdivided in two major categories: abiotic natural capital, such as fossil fuels, minerals and solar energy; and biotic natural capital (or ecosystem capital) that comprises the ecosystem services, essential for human well-being (SOER, 2015).

Ecosystem services

Ecosystem Services are the benefits that people receive from the ecosystem, which can itself be defined as a complex interaction between the non-living environment and living organisms' communities, humans included (MA 2005). ES are usually divided in provisioning services (e.g. water, food), supporting services (e.g. nutrient cycling), regulating services (e.g. floods or climate regulation) and cultural services (e.g. recreational) (Millennium Ecosystem Assessment, 2005).

A concept that is closely correlated with ES is Biodiversity, which is the variability among living organisms, belonging to terrestrial, or aquatic ecosystems and to the ecological complexes that surround them. Established that the diversity of living species has a great value that transcends the human interest, changes in biodiversity can affect the provision of Ecosystem Services (Millennium Ecosystem Assessment, 2005).

Since the ecosystem approach offers an accurate representation of the linkages between people and the environment, the Convention on Biological Diversity (CBD) has stated that said approach helps to use sustainably altogether the living resources, land and water (CBD, 2004). For this approach to be successful, decision makers have to understand the plurality of the effects of a policy or a management change on an ecosystem and therefore, on a number of services provided by that ecosystem. People take advantage of various services coming from ecosystems and it is therefore straightforward to use the ability of an ecosystem to provide the desired services as a portray of the general condition of said ecosystem. Nevertheless, the methods that can be used for such evaluation are numerous. Once those evaluation are available to decision-makers and stakeholders, they have the information they need to take appropriate decisions. On the other hand, the conservation of ecosystems can be hindered by an incorrect or a lack of representation of ES in the market. Oftentimes the cause of the degradation of an ES can be multifactorial; for example it could depend on a strain put on the production of the service due to economic growth or demographic changes (see: urban sprawl) (Millennium Ecosystem Assessment, 2004).

Land use and land cover (LULC)

Land itself can be considered as the most important natural capital, since the majority of human activities occur on land (*Dampha, 2020*). Land cover can be defined as biophysical state of the earth, its immediate subsurface (Ii *et al.*, 1995) and human structures that cover it. (Agarwal *et al.,* 2002; Ali Bah *et al.,* 2019). Since land cover changes are originated mostly by human use (Allen and Barnes *1985;* Turner *et al.,* 1990; Whitby 1992), it is necessary to understand what land use change is. Land use is defined as the kind of anthropogenic activities that are executed on terrestrial surface (*Dampha, 2020*). Land use includes both the reason or purpose behind the land use (e.g. forestry or farmland) and the way the biophysical features are manipulated, that is the way vegetation, soil, and water are treated or modified (e.g. use of irrigation systems or fertilizers). (Ii *et al.*, 1995). Changes in LULC have important environmental implications (Ii *et al.*, 1995) and the sustainability of any land use is not only connected to its environmental features and the techno-managerial strategies used, but also to the socio-economic condition of the area (Arizpe *et al.*, 1994; Blaike and Brookfield 1987). Since LULC is the link between socio-economic aspects of human life and the environment, it's easy to see how a change in LULC can cause a modification of the ecosystem, and therefore in its services (Han *et al.,* 2016; Peng *et al.*, 2021). It is known that with changes in LULC, come significant impacts on ES availability for the future and for this reason, Land Use Land Cover changes can be used to represent and give an idea of what are the impacts that future development or environmental change can have on Ecosystem Services (Lang and Song, 2019; Peng *et al.*, 2021; Yang *et al.,* 2017; Guo *et al.*, 2021).

Urban sprawl

Urban sprawl is a common phenomenon of urban spatial structure that is defined as "the rapid expansion of the geographic extent of cities and towns, often characterized by low-density residential housing, single-use zoning, and increased reliance on the private automobile for transportation" (Rafferty, [2]). It happens as a response to the need to adjust to a rising urban population that many times, is accompanied by the desire for increased living space. (Pourtaherian *et al.*, 2022; Rafferty [2]). As the phenomenon itself is characterized by being an *'excessive'* extension of urban space, or by being *'beyond a specific limit' (Pourtaherian, et al.,* 2022)*,* it's evident how it can be highly impactful on the surrounding environment as the wildlife habitats surrounding the city are the first to be sacrificed to give space to more buildings. At the same time, permeable vegetation and soils are replaced by paved and impermeable surfaces, that increase the risks of floodings. Together with that, suburban areas have generally higher levels of energy consumption and produce more air pollution per capita, due to higher use of vehicles (Rafferty, [2]).

Other great issues of urban sprawl, that are not the focus of this work but cannot be neglected, are the social costs and equality issues, extensively studied by many authors (Nechyba and Walsh, 2002; Elmqvist *et al.*, 2002).

Climate Change (CC)

The term "Climate Change" refers to the long-term shifts in temperatures and weather patterns.

Although some major natural events can cause a climate change (e.g. large volcanic eruptions), the term is usually referred to the changes in climate due to human activities, since its main drivers are the burning of fossil fuels like coal, oil and gas, all human activities [3]. The results of climate change are, between others, increasing temperatures and changes in precipitation patterns, that can affect water yield and soil conservation and lead to environmental problems (Kim *et al.*, 2019; Singh *et al.*, 2016; Trang *et al.*, 2017; Guo *et al.*, 2021). As reported by a NASA study, it is expected that, by 2100, Climate Change will drastically alter Earth's ecosystems, causing increasing competition for survival to both animal and vegetal species [22]. Indeed, CC could change the distributions and biophysical processes of ecosystems, and therefore impact ecosystem services (Parmesan and Yohe, 2003).

Overall CC has decreased food and water security it has caused adverse impacts on human health especially in urban areas, where extreme hot events and extreme climate events have intensified causing morbidity and mortality (IPCC, 20023).

InVEST's models

As mentioned before, the study uses InVEST to evaluate the impacts of CC and LULC change. InVEST is an open-source suite of models that can be used to map and value the goods and services from nature that sustain human life. It is designed to inform decisions about natural resource management, and it can be used to explore how changes in ecosystems are likely to lead to changes in benefits that people receive [4].

InVEST models are available as a standalone application, nevertheless the outputs are shown in a map format, therefore a mapping software (e.g. QGIS) is needed. To run the models, the Python application programming interface (API) provided by NatCap Project was used, as it was faster and more efficient than using the user interface, due to the high number of scenarios studied.

The InVEST version used was Version: 3.12.0 and the documentation is available on the NatCap Project website [5].

InVEST models are based on production functions that explain how changes in an ecosystem's structure are likely to affect the ecosystem services. Hereafter, for each ES assessed in the study, a brief description of the functioning of its model will be provided, while a summary of the data needed will follow in a dedicated subchapter. More in depth information are available in the InVEST user guide [6].

Seasonal Water Yield (SWY)

Stormwater can undergo various processes, including simple evaporation, evapotranspiration by vegetation, runoff to watercourses, and finally the infiltration to the groundwater. The allocation of these flows, which can be simplified by a water balance, is a function of the nature of the environment and the topography and it determines the recharge of the water tables that can be exploited by man.

Service's offer:

InVEST's model "Seasonal Water Yield" (SWY) is used to estimate the effect of landscape management on the water supply service, for uses like irrigation, domestic consumption, and hydropower production. The model seeks to provide guidance regarding the contribution of land parcels to the generation of both baseflow and quickflow. The model computes spatial indices that quantify the relative contribution of a parcel of land to the generation of both baseflow and quickflow. The contribution of a given parcel to streamflow depends on a number of environmental factors including climate, soil, vegetation, slope, and position along the flow path. Depending on the approach taken in regards of the water yield of a single pixel, it's possible to develop a set of three indices, one for quickflow, one for recharge (or 'potential baseflow'), and one for actual baseflow. For each pixel in a territory, precipitation water that is not evapotranspired by vegetation and does not contribute to surface runoff, will seep into the soil, and contribute to local groundwater recharge (L). Once the InVEST model has been implemented, the indicator used to represent the service offer is " L " given in millimetres. Conversion to cubic metres is obtained by multiplying the value by the pixel area $\times 10^{-3}$. Pixel values can be aggregated by sub-watershed, which appears to be the most relevant scale for the representation of services related to hydrological functions. The final indicator is the volume, in cubic metres that contributes to groundwater recharge, per sub-watershed.

Nutrient Delivery Ratio (NDR)

Land use change, especially conversion to agricultural lands, can be very impactful to the natural nutrient cycle. After precipitation events, water flows over the landscape carrying pollutants from these surfaces into streams, rivers, lakes, and the ocean and the presence of high concentration of pollutants in waterbodies can directly affect aquatic ecosystems and people's health (Keeler *et al.*, 2012). The model focuses on Nitrogen and Phosphorous since the quantity of these two nutrients coming from anthropogenic sources (agricultural activities) far exceed the quantities deposited naturally in ecosystems. The modalities of transport of N and P are different: N is mainly transported in the form of nitrate ions, which are washed out, and then pass mainly in subsurface along the slope to the bottom of the valley, while P is mainly transported on the surface in its phosphate form in connection with sediments.

On the other hand, ecosystems can provide a purification service by retaining or degrading pollutants before they enter the stream. For instance, vegetation can remove pollutants by storing them in tissue or releasing them back to the environment as inert gas (denitrification), soils can also store and trap some soluble pollutants (sedimentation) and wetlands can slow the flow long enough for pollutants to be taken up by vegetation. The model offers to land-use planners, the spatial information required on nutrient export and areas with highest filtration. The model provides this information for non-point source pollutants (fertilizers and livestock manure).

Service's offer:

The objective of the InVEST nutrient delivery model is to map nutrient sources from watersheds and their transport to the stream. The retention service is of particular interest for surface water quality issues and can be valued in economic or social terms, such as avoided treatment costs or improved water security through access to clean drinking water.

The NDR model is designed to estimate the amounts of nitrogen (N) and phosphorus (P) retained annually upstream of the river system after a diffuse deposition. Nutrient transport by water is represented by a surface flux (related to sediment transport), and a subsurface flux (dissolved). The biogeochemical processes responsible for nutrient retention (denitrification, pumping by vegetation, etc.) are not explained, but are simplified by material balances; they are assumed to be constant throughout the year, as are the deposits. The model calculates the average annual quantity of nutrients exported based on the loads contained by land use class ($Load_i$), the upstream and downstream flow path, and the maximum capacity an ecosystem can retain (eff).

The NDR is the proportion of nutrients that can be exported downstream of a pixel from the nutrients it receives from upstream. Thus, its calculation considers both the tendency of the medium to retain nutrients and the topographic gradient at the origin of their flow. The end result of the model is the total export of the nutrient that spreads into the sub-watershed.

Urban Cooling (UC)

The phenomenon called "Urban Heat Island" (UHI) affects many cities around the world, with major consequences for human health and wellbeing. The UHI effect, which is the difference between rural and urban temperatures, is a result of the unique characteristics of cities due to the thermal properties of materials used in urban areas, that can store more heat, and the reduction of the cooling effect of vegetation. Vegetation is considered a tool to reduce the intensity of urban heat islands and the thermal discomfort of city dwellers. In fact, it can cool down the temperature in two ways: first, green spaces locally humidify the atmosphere of the city, thus creating an oasis effect, (Oke, 1987) by limiting heat storage in mineral infrastructure. In this way, the main mechanism leading to the night urban heat island, is reduced; secondly, the presence of trees has a significant effect on the daytime radiation balance. Ground cover intercepts solar radiation, providing shade on roads and facades, which limits surface warming (Oke, 1987). On a larger scale, many measurement campaigns have demonstrated the oasis effect of urban parks by recording cooler air temperatures in parks than in surrounding neighbourhoods or the rest of the city, with differences of up to 3-4°C (Ca *et al.* 1998; Jauregui 1990; Eliasson 1996; Spronken-Smith and Oke 1998; Potchter *et al.* 2006).

Service's offer:

The InVEST urban cooling model calculates an index of heat mitigation (HMI) based on the main factors influencing local urban air temperature: shade, evapotranspiration, and albedo effect. The model also represents the spatialized effect of cooling generated by large parks, (Zardo *et al.*, 2017; McDonald *et al.*, 2016) that decreases exponentially with distance to the park boundary. On each pixel, the model calculates a HM (heat mitigation) temperature reduction factor based on the cumulative local cooling (DC) and park effect. In addition, the model represents the effects of mixing by advection (horizontal wind) by a sliding mean algorithm applied on the "local" temperature field. Finally, the density of the buildings plays an important role in night temperatures, as the heat stored during the day is liberated by the buildings at night. Details of equations and input data are available in the InVEST 3.8, Sharp *et al.*, 2020 manual and in the IDEFESE report. For more information on how the model works, refer to the full report at Ademe, Hamel *et al.*, 2020.

Urban Flood Risk Mitigation (UFRM)

Flood hazard comes from different sources, including fluvial flooding, coastal flooding, and stormwater (or urban) flooding. The Urban Flood Risk Mitigation model focuses on the latter. It's known that natural infrastructure can play a role for each of these flood hazards, and concerning stormwater flooding, natural infrastructure operates mainly by reducing runoff production, slowing surface flows, and creating space for water (Stürck *et al.*, 2014).

Service offer:

The InVEST model calculates the runoff reduction, as the amount of runoff retained per pixel compared to the storm volume. For each watershed, it also calculates the potential economic damage by overlaying information on flood extent potential and built infrastructure.

The model works in a similar way to the Water Supply Model (SWY). It depends on the hydrological groups of soils (and therefore their absorption capacity), topography, vegetation characteristics and land use-land cover. The main difference between the two models sits in the time step used: for UFRM it is a thunderstorm event, defined by the user by the amount of rain (equivalent to the volume), while in the SWY model a monthly time step is employed.

For the application in Île de France at current conditions, the rain height is chosen at 30 mm, which corresponds to a ten-year storm. The model calculates storm water retention in m^3 per sub-watershed. Details of equations and input data are available in the InVEST 3.8, Sharp *et al.* (2020) manual and in the IDEFESE report attachment file.

MATERIALS AND METHODS

Research program

The research program followed, consisted of several phases, that will be presented in the following chapter.

Since the research sparked from the desire to continue and deepen the work done previously during the collaboration between CIRED and IDEFESE, the initial step was to study the precedent work and the literature available about InVEST and Ecosystem Services. Considering that the results obtained during the project left the researchers with some concerns on possible mistakes and with the desire of further investigate the results obtained, all the scenarios and models have been run again and the results were compared with the previously obtained. Overall, it was confirmed that, besides some minor errors and some discrepancies due to the use of newer versions of some models, no major mistakes were noticed. Nevertheless, some remarks on future adjustments have been proposed.

The second phase of the research consisted of including Climate Change projections on modelisation. In order to do that, the models offered by InVEST were studied to see whether there was room to include, through the input data required, the role played by Climate Change. Of the 8 models previously used, 4 were considered eligible to include Climate Change information (SWY, NDR, UC, UFRM). The data required was collected and elaborated as needed to run the models, and the four models were run including future projections of urbanisation and climate change, in some cases following Faure's (2018) suggestions.

The results obtained were analyzed and elaborated in order to obtain a visual representation of the variation of the status of the Ecosystem Services between past and present. In this phase, possible future scenarios have been included in the representation and their variation has been calculated taking the year 2017 (the scenario closest to the present) as the reference.

The implications of CC and LULC were further studied by following the methods used by Bai et al (2019), and two indexes, Relative Importance Index (RII) and Cumulative Effect Index (CEI) were calculated to further understand the relationship between LULC change and Climate change.

Finally, to see whether InVEST models are robust enough to seize the impacts of CC and LULC change, and to have an idea of the range of possible future scenarios that should be considered, twelve scenarios were included in the study of the four services considered. The results obtained were compared, to see how much of a difference it makes to work with different projections of demographic growth, different choices of residential solutions and finally, with different Representative Concentration Pathways (RCPs). To have an immediate depiction of the *status quo* the results are summed up through the use of graphs and maps, and their coherence with expectations is discussed on a case-by-case basis.

Description study area

The present study focuses on Paris and the surrounding region of Île-de France (France). The region has a relatively small area of 12,012 km^2, and a population of 12.27 million inhabitants in 2020, that makes it the most popular region in France, hosting 18.8% of the population of metropolitan France. The region is strongly centralized in the Paris agglomeration, which covers 23.7% of the regional area, but where 88.6% of its population lives. Despite the region being highly urbanized, large valleys are present (Seine, Marne, and Oise). The region has large forest masses (285,000 ha) and many large urban parks. Île-de-France is predominantly agricultural and rural in terms of land occupation [7]. About 48% or the region is devoted to agriculture [8] and about 24% to the forest. However, the increase in urbanization, year after year, continues to grow at the expenses of the agricultural area that has lost a thousand square kilometres over the last fifty years in the face of urban sprawl and infrastructure developments [9]. The region is located in the centre of the Paris Basin, irrigated by the river Seine, it has a temperate climate, moderated by oceanic influences. The average temperature is 12°C and the average annual precipitation is 640 mm [10], [11].

Data acquisition: InVEST input data for past and present scenarios

Since the study sparks from a previous work conducted at Cired in collaboration with IDEFESE, the data used to run the scenarios regarding past data were the same used before, and they can be therefore found in the IDEFESE report (Tardieu *et al.*, 2020). Briefly, the sources can be summed up as follows:

Most of the data (DEM, LULC) are available on the National Institute for Geographic and Forest Information (IGN) website [12]. All ES models require input data for land cover layers such as soil cover mode (*Mode d'Occupation du Sol,* MOS) in Île-de-France. The Land Use is a digital inventory of land use in Île-de-France. Its first edition dates from 1982 and is updated approximately every 5 years. The MOS is based on aerial photos covering the entire regional territory, and distinguishes between agricultural, natural, forestry and urban areas (housing, infrastructure, facilities, economic activities, etc.) up to 81 legend positions at the 1/5000 scale. The interactive map of land use and land use differences between 1982 and 2017 can be found on the platform of *Institut Paris Region* [13]. In addition, Theia's website [14] provides high resolution and regularly updated land cover maps.

For the information on sub-watersheds, data are provided by the Public Service of Information about Water [15];

Precipitation and evapotranspiration data is obtained from ALADIN-CNRM, (2018) through the *Météo-France* portal; where ALADIN is a numerical model (*Aire Limitée Adaptation dynamique Développement Inter National*) used at CNRM as Regional Climate Model (RCM) [16].

Data from the Water Framework Directive on the maximum thresholds for nitrate and phosphate to qualify the good condition of surface and ground water bodies.

Culture factors, hydrology groups, and other general parameters are found in literature and adapted to Île de France (Allen *et al.*, 1998; Faure, 2018; Hijmans *et al.*, 2005; Zhang *et al.*, 2009; Tournebize, 2018; Nemery and Garnier, 2003; NRCS 2007; Steward & Oke 2012; APUR 2017), or the default values provided by the InVEST guide are used (Sharp *et al.*, 2020). More specifically, here's a list of data source for each Ecosystem Service used:

Seasonal Water Yield:

- Monthly cumulative precipitation values averaged over the period studied are provided by CNRM 2018;
- Monthly evapotranspiration reference values (ET0) were obtained from ALADIN, *Météo-France*;
- Digital Elevation Model (DEM) is made available at IGN's portal, under the BD alti© section [17];
- Land cover raster (MOS) are available on the IGN's portal;
- Soil hydrology groups (HSG) are found in literature, from De Boer, (2016);
- Vector layer of sub-watersheds can be found at the French national website of water data [15];
- Curve number (CN) obtained from tabulated values for each land use by the four hydrological soil groups, is developed by Natural Resources Conservation Service (NRCS, 2007). In a non-waterproofed urban environment, these values were calibrated using p_{imp} waterproofing rates found at *Institut d'aménagement et d'urbanisme* (IAU, 2018) and averaged within each MOS station concerned;
- A monthly crop factor (Kc), is taken from Allen *et al.* (1998), or recalculated according to the Leaf area Index (Faure, 2018);

Nutrient Delivery Ratio :

- Digital Elevation Model (DEM) is made available at IGN's portal, under the BD alti© section [17];

- Land cover raster (MOS) are available on the IGN's portal;
- The vector layer of sub-watersheds is available at the French website on water data [15];
- Quickflow, taken from the SWY model's output.
- Monthly evapotranspiration reference values (ET0), ALADIN, Météo-France [11];
- Monthly culture factor (Kc), from Allen *et al.*, 1998 or recalculated according to the Leaf area index (Faure, 2018);
- Soil hydrology groups (HSG) from De Boer (2016);
- General parameters (α, β, threshold accumulation flow): α=0.08, β=1, the "Threshold accumulation flow" is taken equal to 1000 according to Sharp *et al.*, (2020);
- Nutrient loading (load_surf) is taken according to Sharp *et al.*, (2020), Hijmans *et al.*, (2005), adapted to Île-de-France;
- Maximum retention efficiency (eff) is taken according to Zhang *et al.*, (2009), adapted to Île-de-France;
- Critical retention length (crit_len): by default, taken equal to 20 m (pixel size on the land use map) from Sharp *et al.*, (2020). For riparian forests and meadows, which have a strong role in nutrient retention, a criterion specific value has been recalculated from the maximum retention efficiency values (Zhang *et al.*, 2009);
- Proportion of subsurface flows is taken at 95% for N, Tournebize, (2018) and 10% for P, (Nemery and Garnier, 2003);
- Borselli K-factor: by default, taken from Sharp *et al.*, (2020);
- Maximum subsurface retention efficiencies, critical subsurface retention length: by default, taken at 0.5 and 20 m respectively, for both nutrients and on the entire map; data from the Water Framework Directive on the maximum thresholds for nitrate and phosphate to qualify the good condition of surface and ground water bodies.

Urban Cooling:

- Land cover raster (MOS) are available on the IGN's portal;
- Reference on evapotranspiration: extracted from the ALADIN model, CNRM;
- Area of interest (AOI): IRIS contour layer, where IRIS are the smallest statistic spatial units [18] or municipalities contour layer (BD GEOFLA®); using a shading factor between 0 and 1, Sharp *et al.* (2020);
- Crop coefficient, defining actual evapotranspiration (Kc);
- Albedo value between 0 and 1. Albedo value for nature spaces is 1 meaning that this type of land use is green, (Steward & Oke 2012; Lavigne *et al.*, 1994; APUR 2017);

- D: maximum distance (m) of the effect of large parks (> 2 ha). Set to 100 m in the Invest model by default;
- Rural reference temperature (T_{ref}): first quantile of the values of the MUSCADE project conducted in Île-de-France (day: 36.02°C; night: 20.72°C) to be readjusted according to location [19];
- UHI_{max}: maximum urban heat island intensity, 99th - first quantile of MUSCADE values (day: 2.05°C; night: 4.66°C) to be readjusted according to location;
- Air temperature maximum blending distance (r_{mix}): radius used in the sliding mean algorithm to correct temperatures. Defaulted to 500m in InVEST software;
- INSEE data on demography at the same scale as the AOI map [24].

Urban Flood Risk Mitigation:

- Land cover raster (MOS) are available on the IGN's portal;
- The vector layer of sub-watersheds is available at the French website on water data [15];
- Rainfall depth: depth of rainfall for the design storm of interest;
- Curve number (CN): tabulated values for each land use according to the four hydrological soil groups (NRCS, 2007).
- Monthly evapotranspiration reference values (ET0), from ALADIN, météo-france [11];
- A monthly culture factor (K_c), from Allen *et al.* (1998);
- Digital Elevation Model (DEM) is made available at IGN's portal, under the BD alti© section [17];
- Soil hydrology groups (HSG), taken from De Boer (2016);
- Map of the flood zones and the populations living there [20].

Future scenarios

To consider the future evolution of the LULC, some scenarios developed during IDEFESE project were further investigated. In fact, for the IDEFESE project, two types of scenarios were used to work on the concept of development: trend and contrasting scenarios. Trend scenarios are based on a forward-looking extension of a dynamic, in this case urbanisation, in order to predict the evolution of land use according to past trends. Contrasting scenarios, on the other hand, are static changes in LULC based on either public policies or needs expressed by stakeholders to demonstrate the impact that could be expected from different planning decisions, they can be seen as hypothetical scenarios (for example land planners want to see what the impact of creating new green spaces in the city centre would be on ES), to this category also unrealistic scenarios can be added (such as changing the LULC of all streets into forests). These kinds of scenarios are created to have a deeper understanding of the relationship between the drivers considered. Since this work focuses on realistic future developments of the region, only trend scenarios have been considered.

In order to model urbanization dynamics, demographic projections of the INSEE were used, together with a model of change of land use affecting the areas that will be urbanized first, in case of population growth. The method investigated in the case of Île-de-France for the land use change model was the “Simple Land Use change Model” (SLUM), an empirical approach based on geographical information systems (GIS) developed under IDEFESE’s project.

SLUM, similarly to the work of Houet (2016), evaluates the relative contribution of four types of growth, to the global urban growth, which is based on the historical urbanisation dynamics. SLUM estimates, a calculated urbanization probability for each cell based on the four growth rules present in Clarke and Gaydos, 1998:

1. spontaneous growth: probability of random urbanization;
2. diffuse growth: the likelihood that a newly urbanized cell will become a radiant urban centre;
3. urban growth in "oil stain": urbanization from urban centres;
4. urban growth driven by access to a road network: urbanization along roads.

Further details can be found on the IDEFESE Report.

Through the combination of demographic projections and the possible type of habitation chosen in the areas of new urbanization, 4 scenarios have been developed:

- High-Rural (HR): it represents the worst-case scenario (WCS), where the highest projection of demographic growth is paired with rural housing, that has the highest level of surface occupation per new resident. They are characterized by large lot sizes, generous setbacks from the street, low density of buildings.
- High-Individual (HI): the highest projection of demographic growth is paired with a less dense type of housing, individual housing units. Medium-density housing provides multiple housing units within a shared structure. These buildings tend to share common infrastructure such as party walls, water mains, parking areas, and green space. Typical examples of medium-density housing include duplexes, triplexes, townhouses, row homes, detached homes with garden suites, etc.
- High-Collective (HC): the highest projection of demographic growth is coupled with the least impactful housing solution, collective housing, or high-density development,

such as high-rise apartment towers have very high density with minimal setbacks and located near a variety of other land uses and transit connections.

- Medium-Individual (MI): a medium level of demographic growth is paired with the individual housing solution, for the purposes of research is considered the best-case scenario of urbanisation (BCS) (Hodge *et al.*, 2021; Ellis, 2004; Song *et al.*, 2004 ; Yang, 2008).

Climate Change data acquisition

To include future climate projections the four InVEST models were studied in order to identify which input data had to be modified.

For the SWY model, the CC impact was depicted by using projections for 2050 for monthly cumulative precipitation, monthly evapotranspiration, and number of precipitation events per month. The data were taken from ALADIN for the period 2040-2060, on DRIAS, as punctual, georeferenced data and they were later elaborated to obtain the input files needed for InVEST.

For the NDR model, following the directions suggested by Faure (2018), the Nitrogen efficiency is recalculated for the wet zones (0.96 instead of 0.8) and the information used for the quickflow (QF) is the QF output files obtained after running the SWY model. For the UC model, the source data affected by CC were Evapotranspiration, the reference Air temperature, which is the average temperature in rural areas, where the urban heat island effect is not observed, and the UHI effect, given by the difference between urban and rural average temperatures. Finally, for the UFRM model, only the rainfall depth was modified, by increasing the initial value by a percentage that represented future projections, as reported in literature. (Jacob *et al.*, 2014 ; [21]).

The entirety of the future climate indicators used (precipitation, evapotranspiration, number of precipitation events, average temperature, etc.) was taken from ALADIN, DRIAS, and for each indicator, three different scenarios were considered: RCP2.6, RCP4.5, RCP8.5 (RCP6.0 was omitted).

The use of Representative Concentration Pathways (RCPs) firstly appeared in the 5th IPCC Report and they are defined as follows:

The RCPs outline four distinct 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs have been formulated using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to predict their consequences for the climate system. The climate projections are then used for impacts and adaptation assessment. The RCPs sum up the range of GHG emissions present in literature; they include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). RCP2.6 is illustrative of scenarios that aim to keep global warming likely below 2°C above pre-industrial temperatures. To do so, the scenarios are characterized by substantial net negative emissions by 2100. On the other hand, when considering scenarios without additional efforts to constrain emissions ('baseline scenarios') it's best to refer to pathways ranging between RCP6.0 and RCP8.5.

Output collection for historical representation

Once all the models were run, the results were aggregated per area of interest (summed or averaged) with the aim of obtaining coherent results throughout the time span considered, that made it possible to compare the ES status between the years, and that allowed to create a visual representation of the trends of the ES.

The results are, as aforementioned summed and or averaged, and the variation of the ES's level is calculated taking 2017 as reference year. The data is then listed in a table, and finally, for each ES, a chart representing the ES's status over time is created.

The values taken as indicators are:

- SWY: Local Recharge, the part of water that is retained by the soil and recharges the aquifer. The higher the Local Recharge, the better the service works.
- NDR: following the same choices made during the IDEDESE project, to interpret the conversions of agricultural areas in terms of ES, it was used as output of the model, the ability of ecosystems to retain nutrients independently from the yearly load. With this in mind, the fraction of retention for each year was calculated as follows:

$$Fraction\ of\ retention_i = \left(1 - \frac{Exports_i}{Loads_i}\right)$$

  The fraction of retention of year i is then calculated on the basis of the total exports and load for each year. The final indicator represents the portion of nutrient that is retained by the land in terms of fraction. This value will change with changes in land cover and land use. The higher the portion of nutrient retained, the better the service works.

- UC: Heat Mitigation index (HMI) that considers both the cooling capacity and the proximity of large green areas. The higher the mitigation index, the better the service works.
- UFRM: Flood volume, the lower the volume, the better the service works.

RII and CEI

As reported by Bai *et al.* (2019), the combined effects and relative importance of LULC and climate changes on ES can be evaluated by working on various scenarios with different conditions for both the drivers. For this reason, four scenarios were created, that combined two periods of land use and climate data (1999 and 2050). Scenario 1, the baseline, was based on real environmental conditions in 1999. Scenario 4 was based on projected environmental conditions in 2050. In contrast, in scenario 2, climate was kept the same as 1999, leaving land use change as the sole driver affecting changes in ecosystem services. In scenario 3, land cover remained the same as in 1999, leaving only the effects of climate change to relate to changes in ecosystem services. This way it's possible to separate the impacts of the two drivers of change on ecosystem service provision. Two indicators were used: a relative importance index (RII) and a combined effect index (CEI). And they were used to evaluate all four of the models used in this research. RII reflects the relative influence of the two factors on ecosystem services. A value greater than 0 indicates that LULC change has a greater relative importance than climate change. A value lower than 0 indicates CC has greater relative importance than land use change, and a value of 0 indicates that the influence of both factors is equal. RII is calculated as:

$$RII = \frac{|ES_{scenario2} - ES_{scenario1}| - |ES_{scenario3} - ES_{scenario1}|}{ES_{scenario1}}, \begin{cases} > 0, Landuse \\ = 0, Equal \\ < 0, Climate \end{cases}$$

CEI reflects the combined effects of climate and land use factors on ecosystem service provision. A value greater than 0 indicates land use and climate factors have an inhibitory effect on ecosystem service. A value lower than 0 indicates land use and climate factors have a synergistic effect on ecosystem service. A value of 0 indicates a state independent from the effects of these variables. CEI is calculated as:

$$CEI = \frac{ES_{scenario2} + ES_{scenario3} - ES_{scenario1} - ES_{scenario4}}{ES_{scenario1}}, \begin{cases} > 0, & Inhibitory \\ = 0, & Independant \\ < 0, & Synergistic \end{cases}$$

where, $ES_{scenario1}$, $ES_{scenario2}$, $ES_{scenario3}$, $ES_{scenario4}$ represents the value of sole or aggregated ecosystem services in each scenario set.

Robustness

In order to understand if InVEST is suited to include CC in the evaluation of ES, the output maps for each ES will be qualitatively and visually compared and the magnitude of changes in the ES's status will be qualitatively evaluated comparing 12 different scenarios, which are a combination of the prediction of mild and high demographic growth, three scenarios of housing solution for the new buildings (Collective, Individual and Rural), and three RCPs (RCP2.6, RCP 4.5 and RCP8.5). The scenarios have been named as follows:

- HI 2.6: high demographic growth, individual housing, RCP2.6;
- HI 4.5: high demographic growth, individual housing, RCP 4.5;
- HI 8.5: high demographic growth, individual housing, RCP8.5;
- HR 2.6: high demographic growth, rural housing, RCP2.6;
- HR 4.5: high demographic growth, rural housing, RCP 4.5;
- HR 8.5: high demographic growth, rural housing, RCP8.5;
- HC 2.6: high demographic growth, collective housing, RCP2.6;
- HC 4.5: high demographic growth, collective housing, RCP 4.5;
- HC 8.5: high demographic growth, collective housing, RCP8.5;
- MI 2.6: mild demographic growth, individual housing, RCP2.6;
- MI 4.5: mild demographic growth, individual housing, RCP 4.5;
- MI 8.5: mild demographic growth, individual housing, RCP8.5.

For each ES studied, all 12 the scenarios have been compared by calculating an indicator for the status of each ES, as done also for the RII and CEI evaluation. The indicators have been compared qualitatively through the use of graphs, to see if and how the ES statuses changes according to the 3 drivers considered and what trends can be highlighted in each Ecosystem Service.

RESULTS

Land use change and Climate change

In order to understand the magnitude of change in the services provided by the ecosystem, it is useful to have some information on the modification that happened in the area studied and at the same time it is important to provide an insight on how the climatic conditions changed from 1982 until now and how they are expected to change in future.

Three timestamps have been used to show the evolution of the two drivers from the past, to the present and then to the future: respectively years 1982, 2017, and the future scenario referred as ‘HI4.5’ that represents an in-between for the future scenarios used.

Although changes in land use are noticeable in the whole region, especially if we look in proximity of roads, the main area where the urbanisation process is taking place is, as expected, around the city of Paris.

Figure 1 shows how the land use changed in the 70 years considered by the study. The general trend can be described as a substitution of land use, from agricultural uses and forests to urban areas, resulting consequently in an increase in urban areas.

Figure 2 show how average temperatures are distributed across the region for the years 1982, 2017 and 2050 (RCP4.5). Overall it is noticeable a slight decrease in the average temperatures between 1982 and 2017, but in both the years the average temperatures go from 22°C to 27°C. When the first two maps are compared to the projected average temperature in 2050, a relatively large discrepancy can be seen. In fact for the year 2050 the temperatures range from 20°C to 29°C with an increase of 1 or 2 degrees in many areas of the region and a decrease in the average temperature of 1°C in the parks or forest of the region. The following set of maps (Figure 3**)** shows the anomalies in the considered years from the average temperatures. Once again, the anomalies fall in the same range, from +2°C to +6°C, for the first two maps, while they are almost doubled when considering year 2050 with the scenario RCP4.5, where the anomalies range from a minimum of +5°C to a maximum of +13°C.

To see how the data on precipitation changes according to the scenarios considered, Figures 4, 5, 6 and 7 show the amount of precipitation (in millimetres) for the years 2017 and 2050 (RCP4.5) in the months of July and December. Overall the average precipitation in the month of July is more homogeneous in 2017, while for the future projections, there is a higher variability in the average precipitation between the west and east parts of the region, where the average millimetres of precipitation are at their lowest. Comparing the maps for the month of

December, again it easy to see more intense precipitations and a higher variability in the maps showing future scenario, while in 2017 the average precipitations are overall less intense and more uniform across the region.

Finally for the UFRM model, the only information dependent on climate condition was millimetres of precipitation during a storm. For the data concerning the past years, until 2017, the same input value used by IDEFESE was implemented, while when looking at the year 2050 with RCP 4.5 the amount of precipitation assumed was 25% higher than the baseline value. For the specific case, the value was 30 mm for the period 1982-2017 and 37.5 mm for RCP4.5 [21].

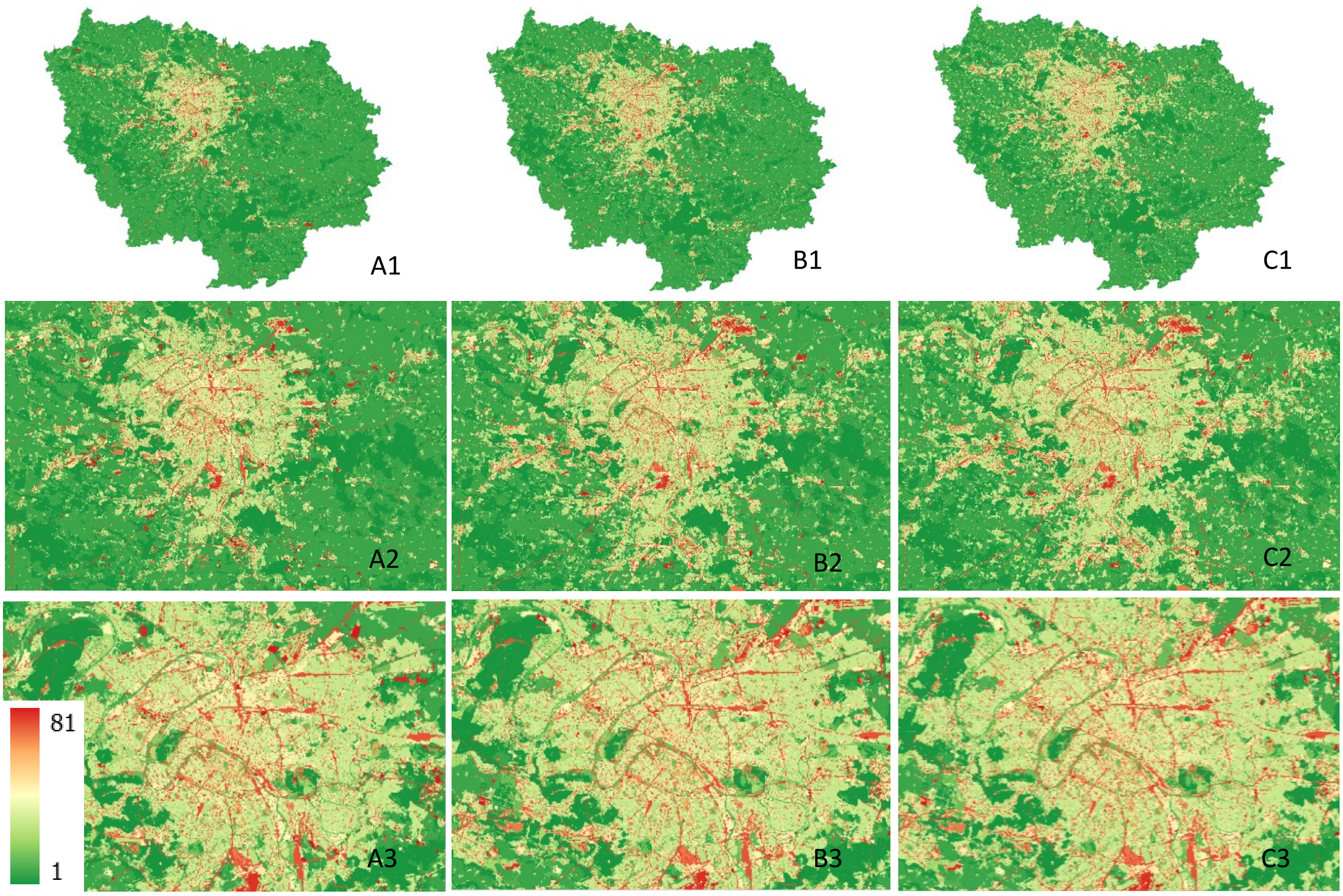


FIGURE 1 Representation of land use in years: A) 1982; B) 2017; C) 2050 scenario HI4.5. At different scales : 1) Île-de-France 2) Petite Couronne 3) Paris. Land use classes go from the less urbanized areas (1) to the more urbanized areas (81).

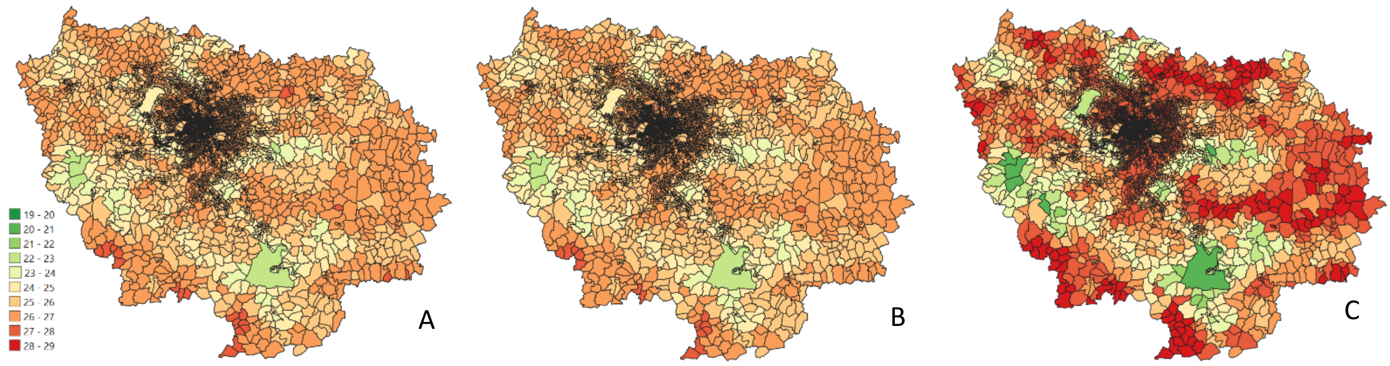


FIGURE 2 Average temperatures in Île-de-France, for years: A) 1982; B) 2017; C) 2050 scenario HI4.5. The temperature varies between 19°C and 29°C.

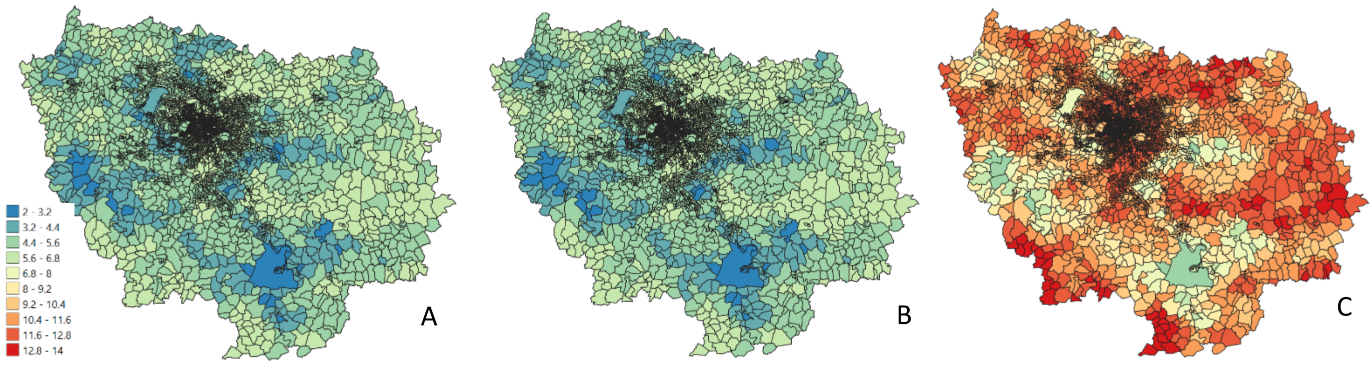


FIGURE 3 Average precipitations in Île-de-France, for years: A) 1982; B) 2017; C) 2050 scenario HI4.5. The precipitation varies between 2 mm and 14 mm.

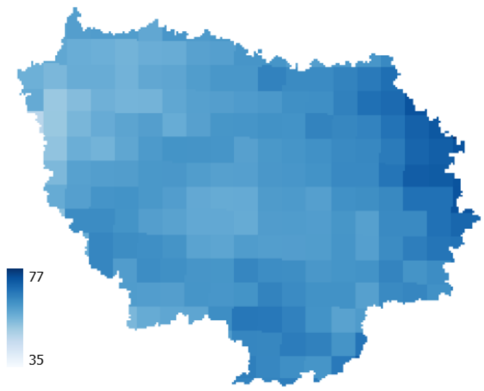


FIGURE 4 Precipitation in July 2050 (RCP4.5) [mm]

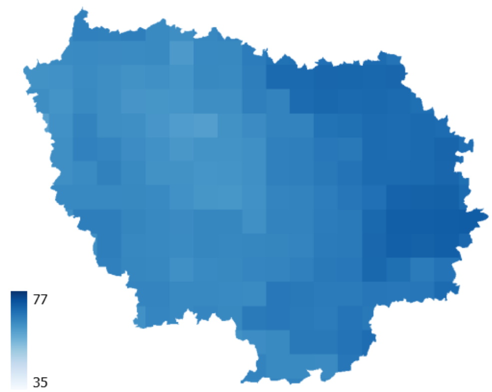


FIGURE 5 Precipitation in July 2017 [mm]

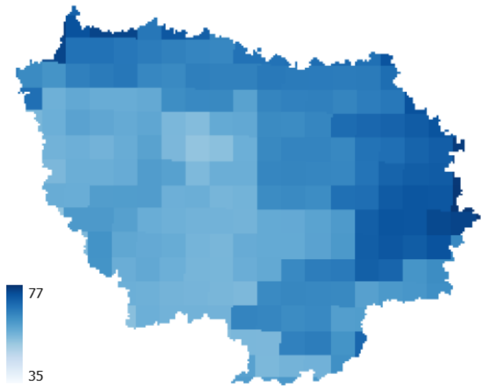


FIGURE 6 Precipitation in December 2050 (RCP4.5) [mm]

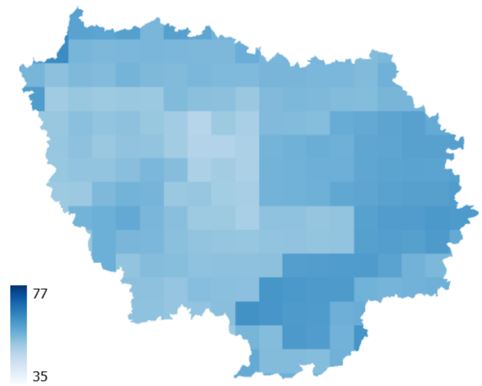


FIGURE 7 Precipitation in December 2017 [mm]

Seasonal Water Yield

Past, present and future

The first Ecosystem Service analysed was the seasonal water yield. The indicator considered as reference was the groundwater recharge. The averaged value of groundwater recharge per watershed in 2017 was 16.5 million cubic meters, which denotes a 11% increase in the recharge volume of 1982 while the total recharge amounts to 11.5 billion cubic meters (Figure 8). With the considered projections of climate and land use change, a reduction of the water retention of 76% was found, due to the impermeabilization of large part of what once was permeable soil and to the modification of precipitation's patterns and frequency (Figure 9).

When looking at the maps, (Figure 10) it's evident how drastic the projected reduction of groundwater recharge is. On the other hand, by looking at the bottom part of the picture, it's noticeable that although the amount of recharge changes between 2017 and 2050, the areas that have the highest values of groundwater recharge, which are the one represented with the darker colours, are still the same and correspond to the less urbanized areas of the region. Overall there is a decrease in water retention in the whole region. The areas that have the lowest values of water retention, are the central and the northern part of the region, that correspond to the most urbanised areas of the region.

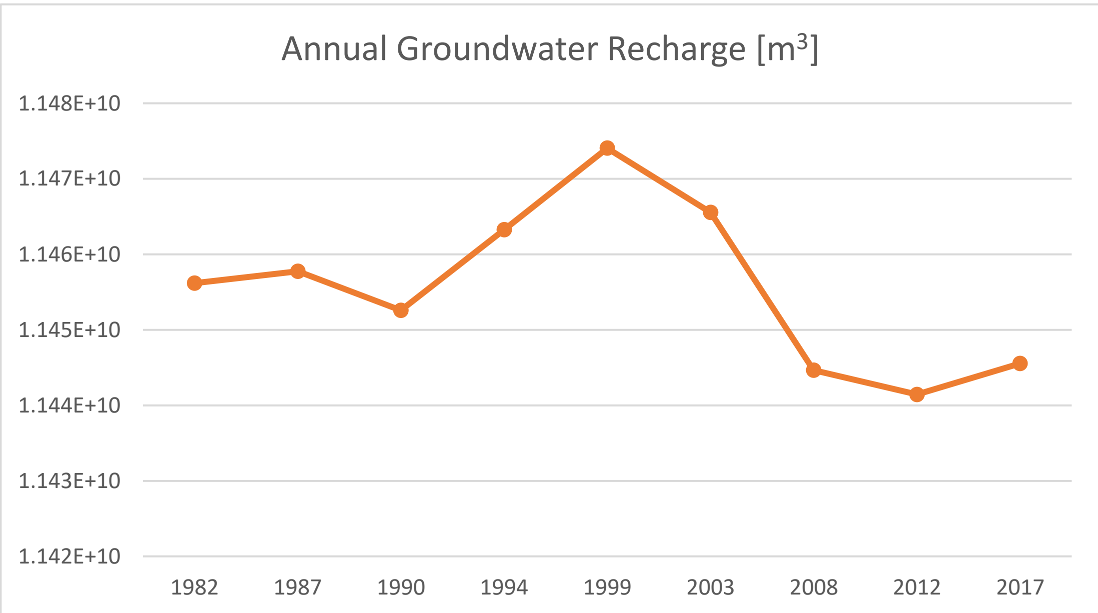


FIGURE 8 Total value of groundwater recharge per year

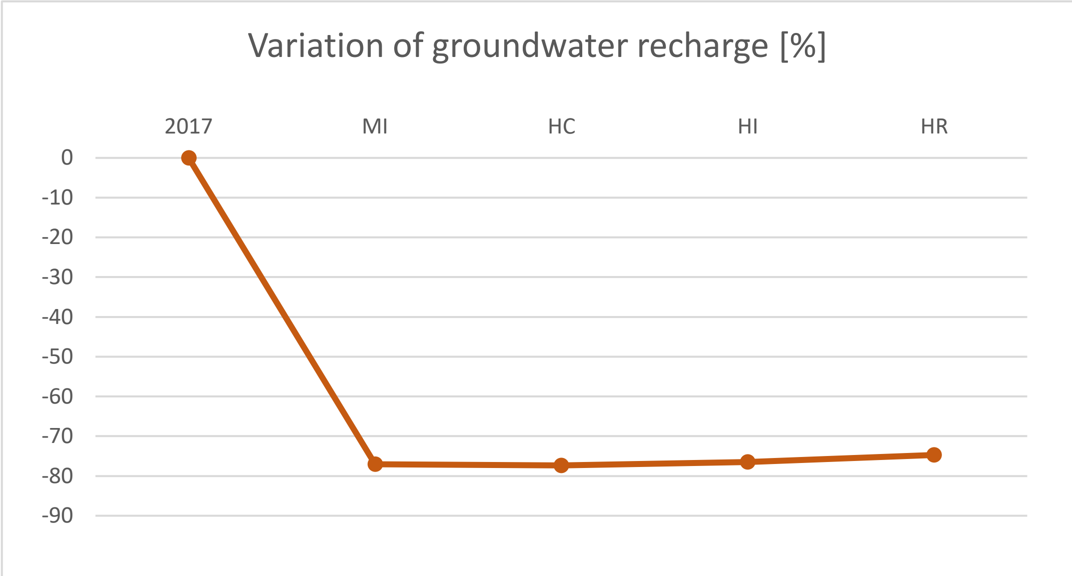


FIGURE 9 Percentage of variation of groundwater recharge from reference year (2017)

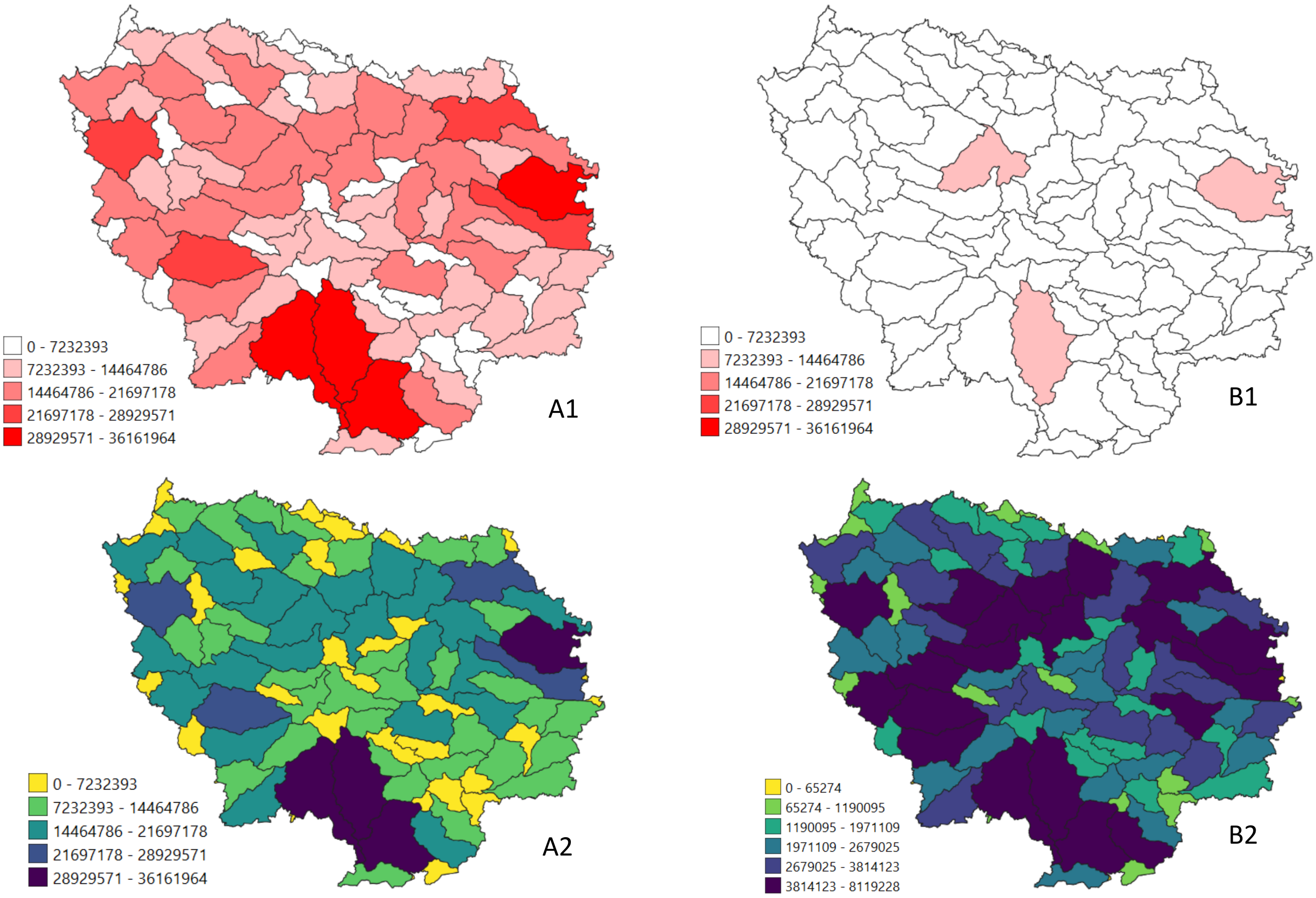


FIGURE 10 Groundwater recharge [m^3] for years: A) 2017; B) 2050 scenario HI4.5. With absolute (1) and relative (2) scales.

Relative importance and combined effect of land use and climate change

In order to understand the relationship and impacts of Land Use and Climate Change, four scenarios were created: a baseline scenario, using land use and climate information of 1999, a future scenario, using projection of high demographic growth and choosing individual housing as the preferred residence solution, and two intermediate scenarios. Once the cumulative indicator of the status of Seasonal Water Year was obtained by calculating the weighted average of groundwater recharge per sub-watershed area, it was possible to calculate the Relative Importance index and the Cumulative Effect index. The value of the RII found was -0.8 indicating that climate has greater relative importance than land use change. The same result has been found when calculating the Relative importance for each watershed: the relative importance of climate change was indeed greater than the relative importance of land use change for all the 117 sub-watersheds in which the region is subdivided.

In a similar way, the combine effect index reflects the cumulative effects of climate and land use factors on ecosystem service provision in each pixel, depending on the value of the index it's possible to say whether the two factors considered have an inhibitory, synergistic or an independent effect on the ecosystem service. In the case of the Île de France, the overall combined effect found was equal to -0.01 which indicates a weak synergistic effect between the two factors considered.

More specifically, when calculating the CEI for each sub-watershed, it was found that in the 90.5% of the sub-watershed a synergistic relationship was encountered, for the 6% of the sub-watersheds an inhibitory effect was encountered and finally for the 3.5% of the sub-watersheds the two factors' effects were evaluated as independent one from the other.

Two opposed possibilities would suggest that the land use change and the climate change have an inhibitory effect: the first one would happen if in the area of interest, there is at the same time a land use change from urbanised to non-urbanised areas coupled with a decrease in the precipitations; the second possibility, which due to the circumstances is also considered as the most plausible, would be that although the urbanization grows, there is at the same time a increase in the total precipitations in the sub-watershed, that inhibits the effect of the impermeabilization of the soil.

Comparison of future scenarios: Land Use and Climatic component

As it was explained in the previous chapter, twelve future scenarios were created and compared considering the combinations of three climatic scenarios and four land use scenarios.

As far as the Seasonal Water Yield model is concerned, Figure 11 shows how, depending on the two factors considered, the total Groundwater Recharge can change.

It's evident how the total volume of water retention changes depending on the land use change, having the lowest values with the scenario HC (high demographic growth, collective housing) and the highest value with the scenario HR (high demographic growth, rural housing), at the same time, for each land use option, the total water retain is the highest with the RCP 2.6 ("very stringent" pathway, likely to keep global temperature rise below 2°C by 2100), while it is the lowest with RCP 8.5 (taken as the worst-case for climate change scenarios). The variation between the highest and lowest levels of water retention is 14%.

Nevertheless, it is very important to notice that, looking at the geographical representation of the region and its sub-watershed, (Figure 12) it is possible to see how overall the extreme values increase going from the best case scenario (MI26) to the worst case scenario (HR8.5) going from a situation in which there is not a high discrepancy in the volume of retained water from one sub-watershed to another, to a situation where adjacent sub-watersheds have large difference in the groundwater recharge.

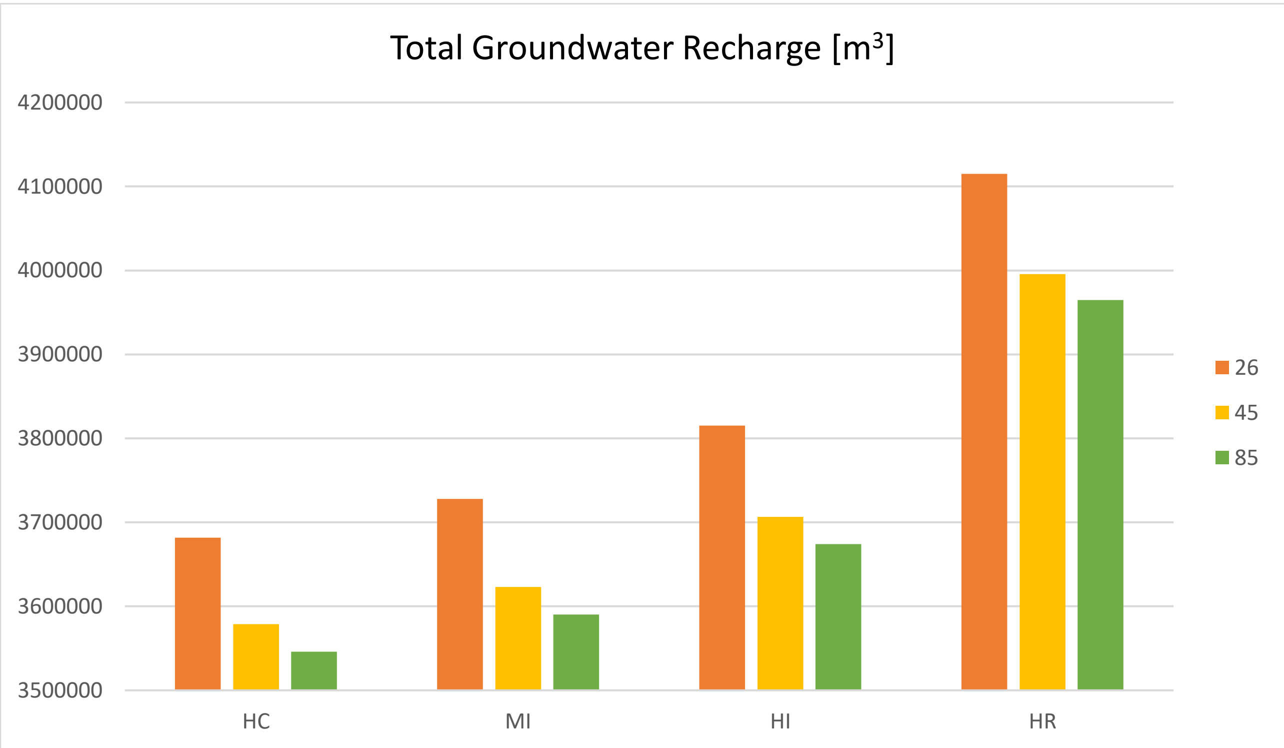


FIGURE 11 Total groundwater recharge for 12 possible future scenarios.

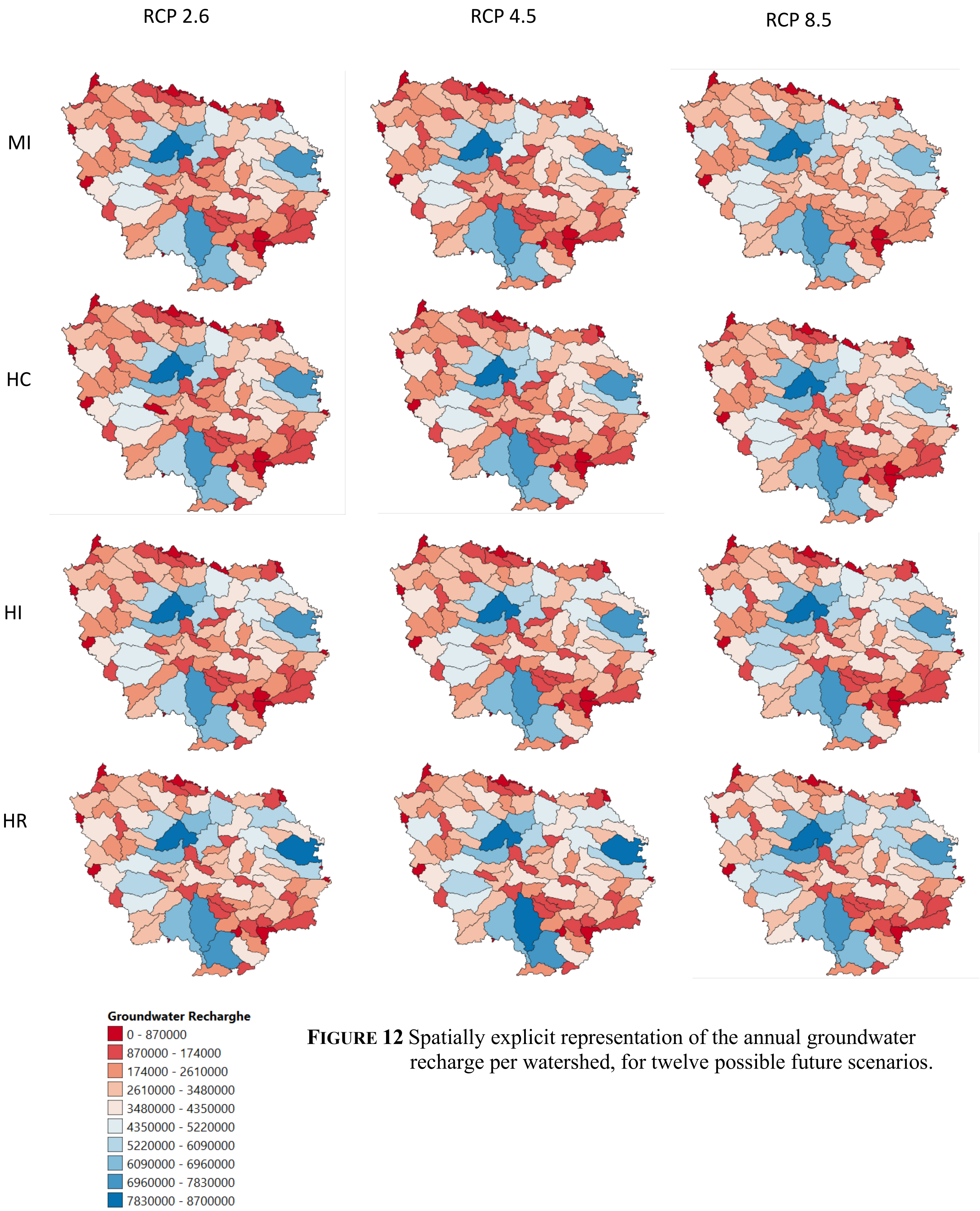


FIGURE 12 Spatially explicit representation of the annual groundwater recharge per watershed, for twelve possible future scenarios.

Nutrient Delivery Ratio

Past present and future

Two indicators have been considered to understand how the Ecosystem service 'Nutrient Delivery Ratio' reacts to changes: the indicator used was the fraction of retention for both Nitrogen and Phosphorous, as the way the two nutrients are retained by the soil is slightly different: while it's assumed by the model that phosphorous has only a superficial flow, for nitrogen two flows are considered, a superficial and a sub-superficial one. Therefore, the fraction of retention (FR) for nitrogen is calculated from the sum of the two flows.

The average percentage of nutrient retention for the watershed considered in 2017 was 50.86% for Nitrogen and 87.50% for Phosphorous, while considering the projections for year 2050, for the land use scenario "4.5", the percentages of retention for Nitrogen dropped to a value between 50.38% and 50.42% depending on the land use scenario considered, inverting the trend of growth that can be seen in Figure 13, and arriving at a percentage of retention lower than the one calculated for the year 1982. Looking at the retention of Phosphorous, for the year 2050 percentage dropped to a value between 86.36% and 87.16%, the lowest found for the period considered. In 1982 the percentage of phosphorous retention was found at 87.77% (Figure 14).

Observing the average values spatially per sub-watershed (Figure 15) in the three years taken as reference (1892, 2017, 2050) it's evident that, despite some decreases in the level of nitrogen retention for some sub-watersheds, there isn't a great difference between the 3 maps to be noticed, not even at the sub-watershed level. The maps expressing the phosphorous retention (Figure 16), show a slightly more evident decrease in the retention, spread all-over the region.

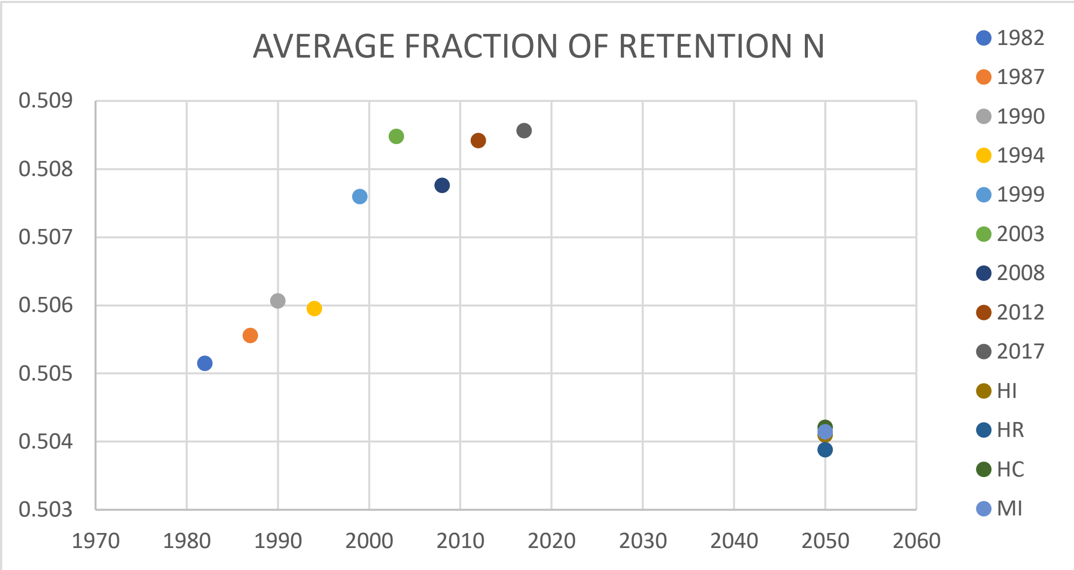


FIGURE 13 Average fraction of Nitrogen retention per year.

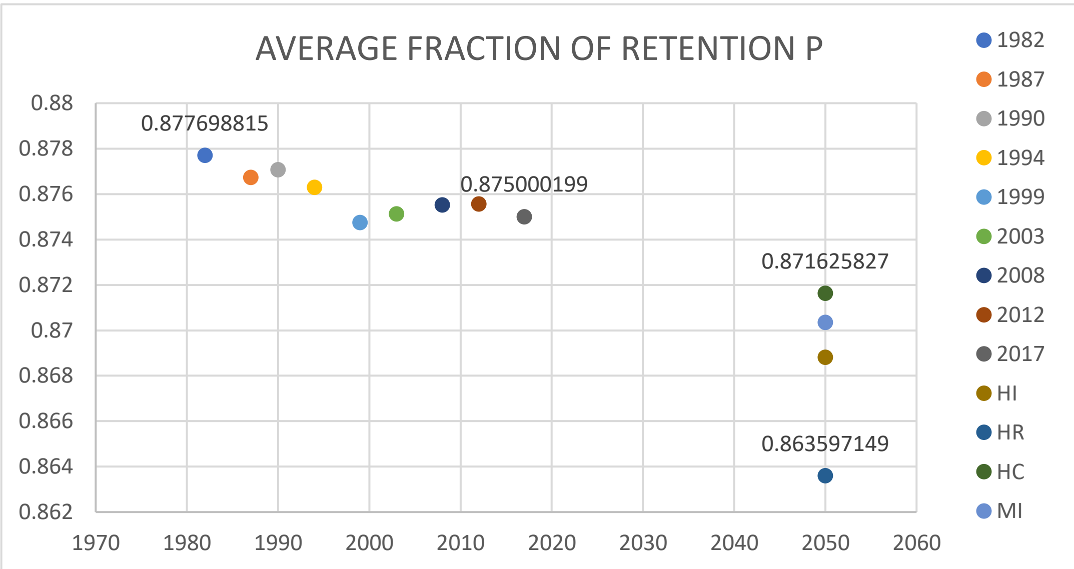


FIGURE 14 Average fraction of Phosphorous retention per year.

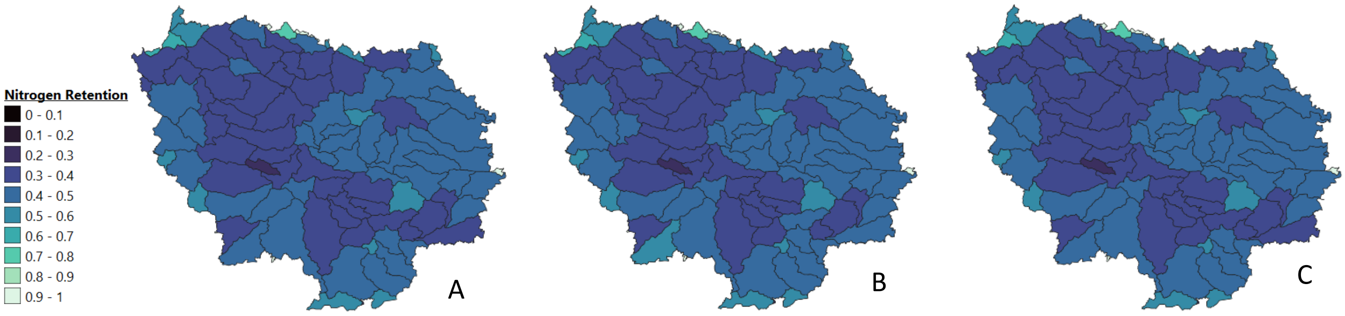


FIGURE 15 Spatially explicit representation of the fraction of Nitrogen retention per sub-watershed, for the years: A) 1982; B) 2017; C) 2050 scenario HI4.5.

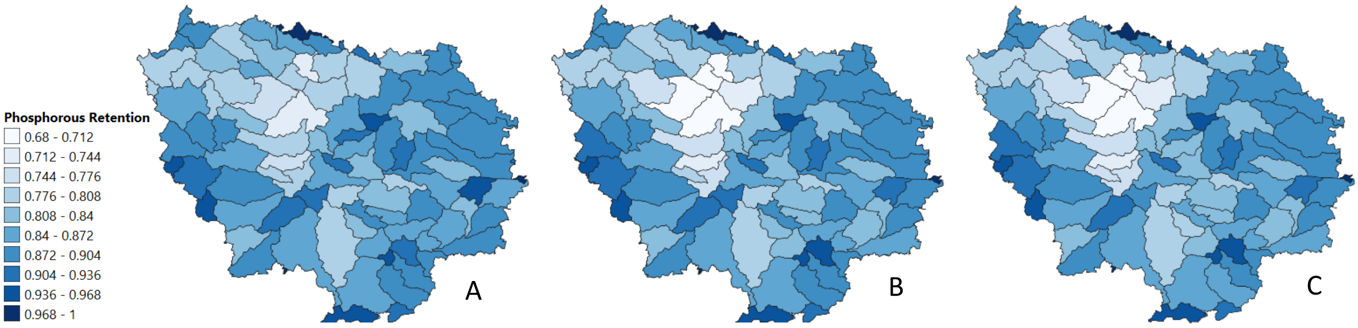


FIGURE 16 Spatially explicit representation of the fraction of Nitrogen retention per sub-watershed, for the years: A) 1982; B) 2017; C) 2050 scenario HI4.5.

Relative importance and combined effect of land use and climate change

The relative importance index calculated for the whole watershed, from the nitrogen fraction of retention was -0.009, a value that suggests that, even if just for a little margin, climate is relatively more important than land use change. Even smaller is the value of RII for phosphorous, 0.002, that suggests that land use change is slightly more important than climate change, when considering phosphorous retention. For the cumulative effect indices, for both N and P, the values are respectively -0.002 and 0.001 theoretically indicating an inhibitory effect between LUC and CC for Nitrogen, and a synergistic effect of the two factors for Phosphorous, nevertheless, the CEIs are so little that the effects of the two factors can be considered independent from one another for the ES studied.

The evaluation of RII for Nitrogen per sub-watershed shows that for the 96% of the sub-watershed climate change is relatively more important that land use change, for 2% of sub-watersheds land use change is more important and for the remaining 2% they have the same importance.

The CEI for Nitrogen at the sub-watershed level is divided in half, with approximately the 50% of the indices that are positive and 50% negative, yet again the CEIs' value is never bigger than 0.045 nor smaller than -0.077 suggesting a weak cumulative effect of the two factors.

For Phosphorous retention, 95.24% of the sub-watersheds had a negative RII, in line with the RII found when considering the watershed in its entirety, for the 2.86% of the sub-watersheds LUC was more important than Climate change, and for the remaining 1.90% their impact was equal. Again for the 42.86% of the sub-watersheds, the CEI indicates a inhibitory effect, 54.28% a synergistic effect and for the remaining 2.86 a neutral effect was found for the two factors.

Comparison of future scenarios: Land Use and Climatic component

The juxtaposition of the twelve future scenarios (Figure 17) shows an evident impact of the choice of the land use scenario for Phosphorous retention, where the less land is urbanised, the more Phosphorous is retained. The same thing cannot be said for Nitrogen retention, where it seems that land use scenarios do not influence the percentage of Nitrogen retained, as can be seen in Figure 18.

For what concerns the climate scenarios considered, the RCP4.5 appears to be the less impactful on the retention of both nutrients, followed by RCP8.5 and lastly RCP2.6 that has the lowest percentage of nutrients retention. Overall, the scenario that has the highest nutrient retention of the twelve considered is HC4.5, where high demographic growth and collective housing solution, is paired with RCP4.5, and the scenario with the lowest retention capacity is HR2.6, where the high demographic growth and the rural housing solution is paired with RCP 2.6.

Looking at the spatially explicit representation of the possible future scenarios, where the fraction of nutrient retention is averaged at a sub-watershed level, its noticeable that the central most urbanized areas of the region are the ones with a lower value of nutrients retention. The difference between one scenario and the other is subtle and overall uniform and gradual, with no major differences to note for the same sub-watershed, in the different scenarios (Figures 19, 20).

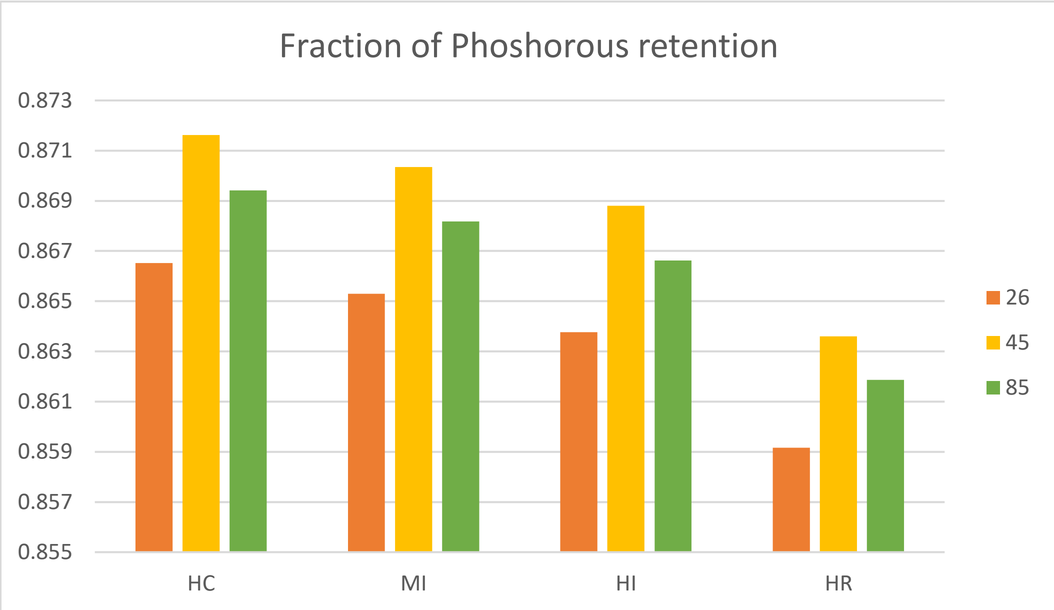


FIGURE 17 Fraction of Phosphorous retention for twelve possible future scenarios.

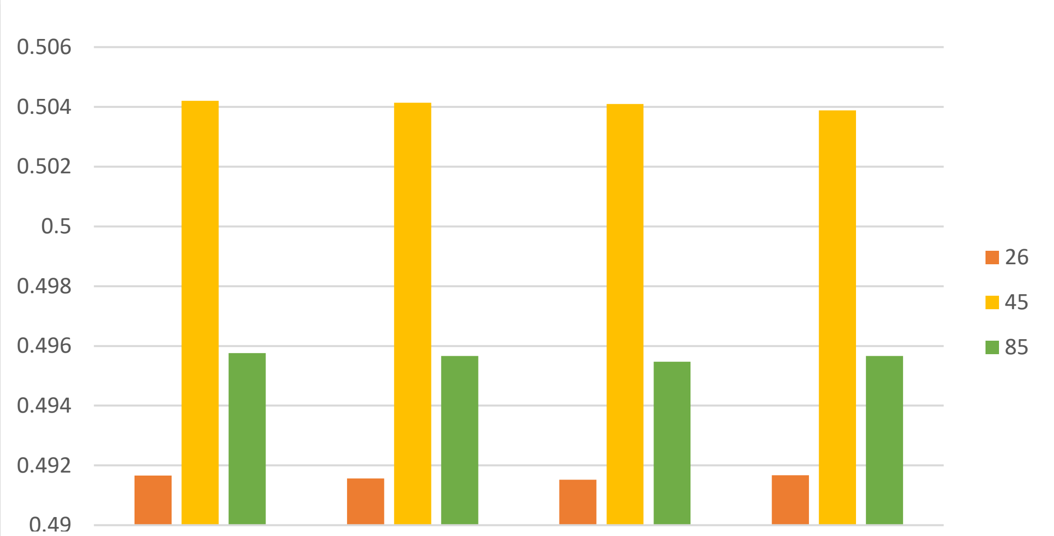


FIGURE 18 Fraction of Nitrogen retention for twelve possible future scenarios.

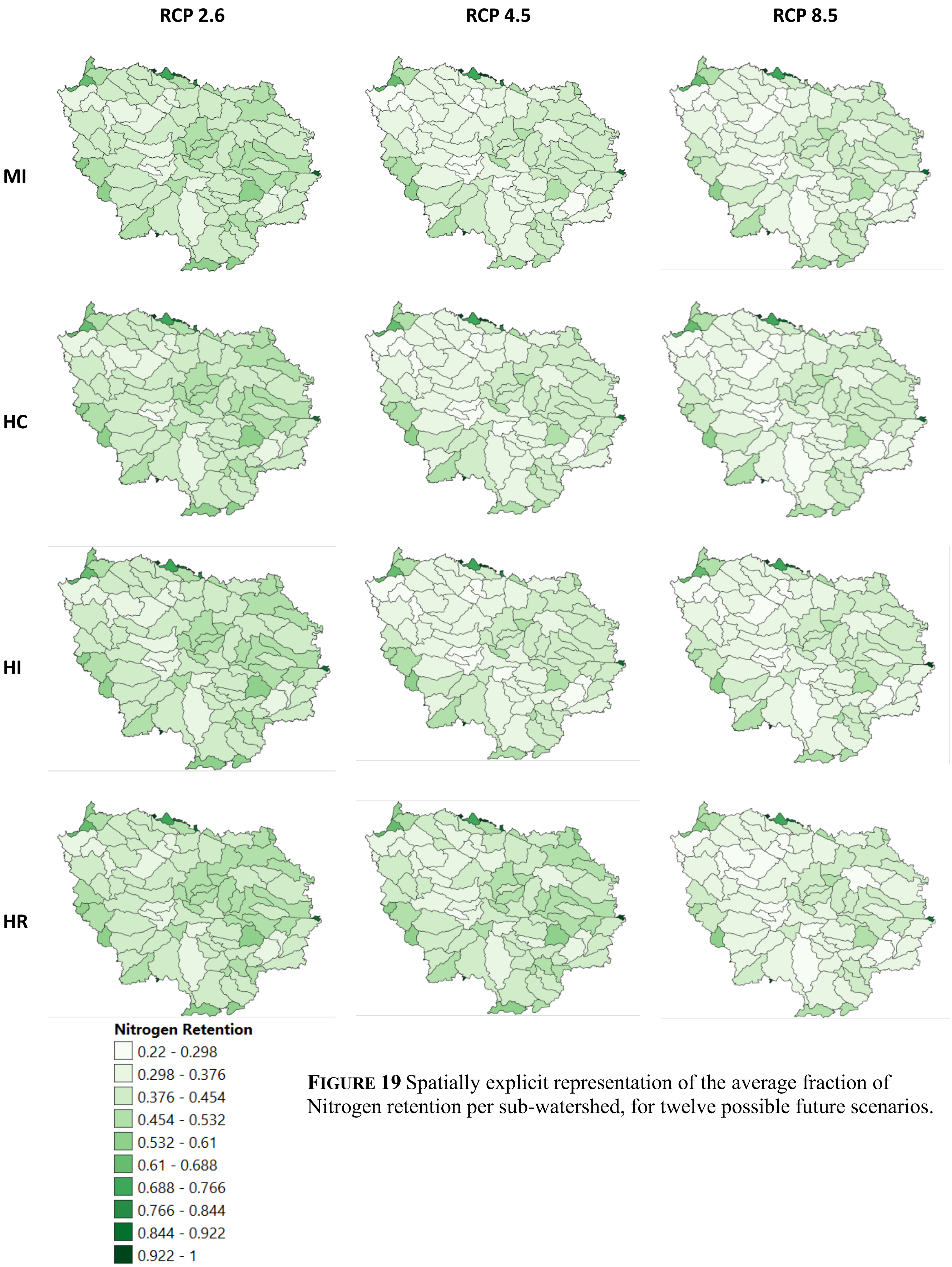
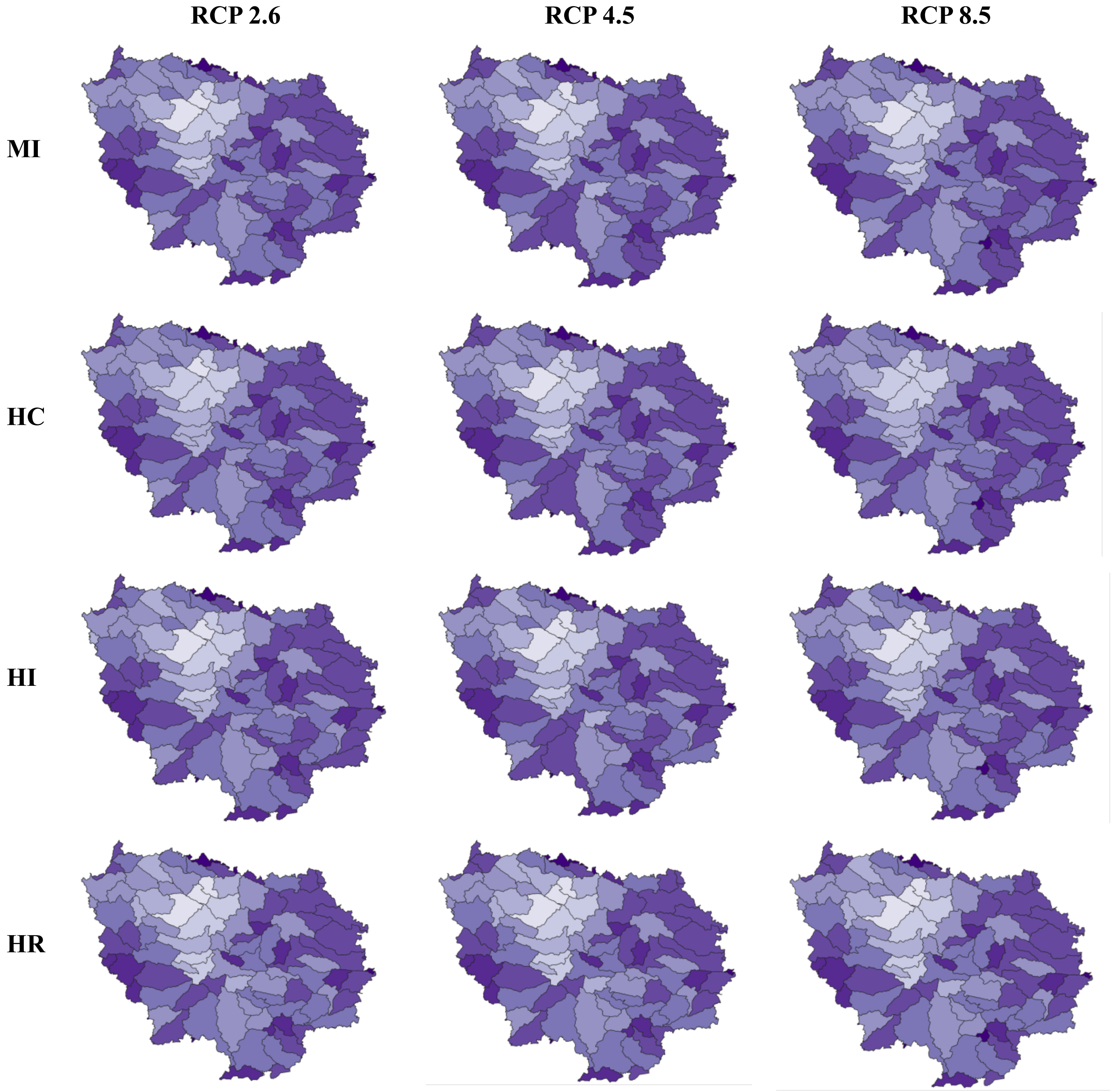


FIGURE 19 Spatially explicit representation of the average fraction of Nitrogen retention per sub-watershed, for twelve possible future scenarios.



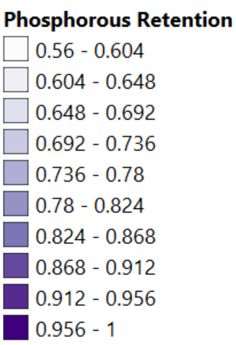


FIGURE 20 Spatially explicit representation of the average fraction of Phosphorous retention per sub-watershed, for twelve possible future scenarios.

Urban Flood Risk Mitigation

Past present and future

The status of the Urban Flood Risk Mitigation was evaluated using Invest for the period between 1982 and 2017 and by using future projection of Land use and climate status for year 2050. The indicator considered was the Volume of Runoff Retention [m^3] aggregated per sub-watershed or for the total region.

Overall the total volume water retention doesn't undergo major changes in the period considered (1982-2017) (Figure 21) and consequently the variation from the reference year is very little (from 0.1% to -0.2). Furthermore, from the data analysed, it's not possible to clearly identify a trend in the amount of runoff retained. When looking at the variation from the reference year for future projections, the results show a 16% increase in the amount of water retained.

The maps (Figure 21) of the volume of retained water show no difference between the years 1982 and 2017, while an overall increase in the volume of water retained can be seen when comparing the abovementioned maps to the projected retention values for year 2050 (Figure 22).

Relative importance and combined effect of land use and climate change

Overall the relative importance index calculated for the whole region, showed that climate change is more important than land use change, and that for the urban flood risk mitigation, the relationship between the two factors is slightly synergistic.

With a closer look to the sub-watersheds it was found that the 91.9% of the sub-watershed climate change was relatively more important than land use change for the ecosystem service studied, while for the remaining 8.1% of the sub-watersheds, the two factors had the same importance. There was no sub-watershed indicating that for the water retention volume, land use is more important than climate change.

The combined effect at sub-regional level showed that for 9% of the sub-watersheds, the two factors have an inhibitory effect, for the 62.2% there's a synergy between the land use change and climate change and for the remaining 28.8% of the sub-watersheds no cumulative effect is found. (Figure 23).

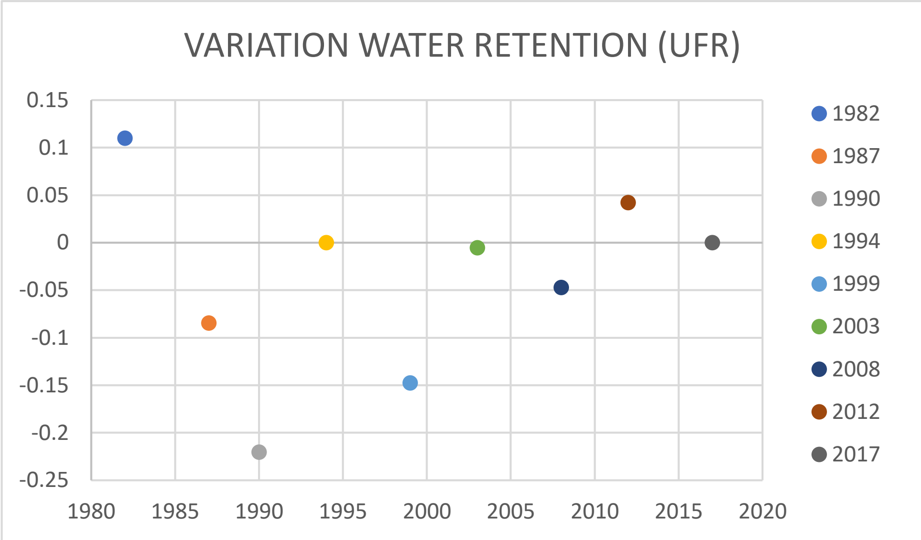


FIGURE 21 Variation from the reference year of the total runoff retention for Île-de-France, from 1982 to 2017.

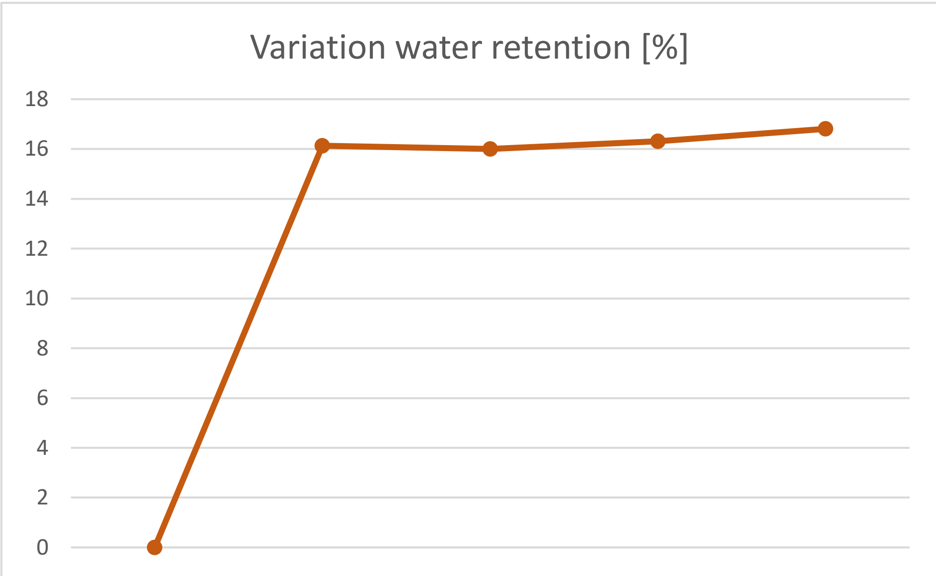


FIGURE 22 Variation from the reference year of the total runoff retention for Île-de-France, depending on the scenario considered (MI4.5, HC4.5, HI4.5, HR4.5).

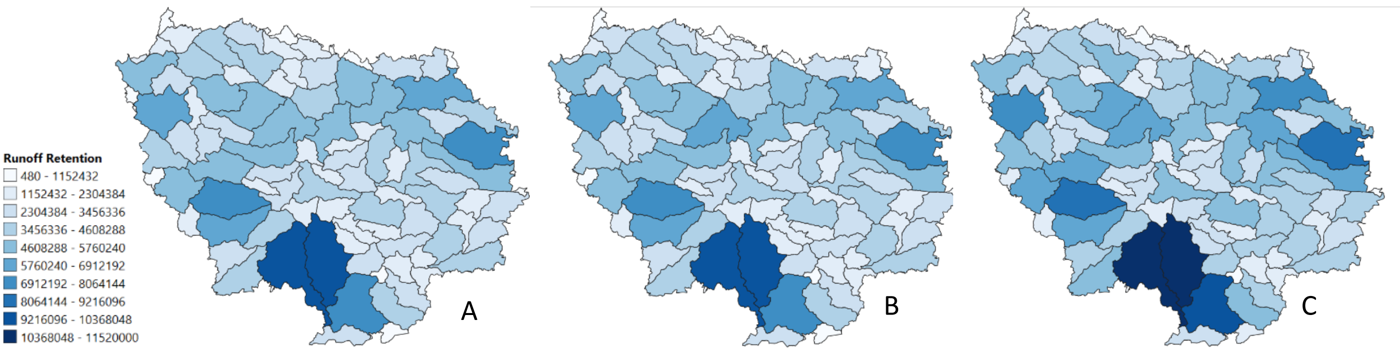


FIGURE 23 Spatially explicit representation of the runoff retention [m^3] per sub-watershed, for the years: A) 1982; B) 2017; C) 2050 scenario HI4.5.

Comparison of future scenarios: Land Use and Climatic component

Between the twelve land use scenarios there is minimal change, having a higher water retention for the scenarios characterized by rural housing solution and the smallest water retention is found in the scenarios where we have a contained demographic growth and individual housing solution.

The volume of runoff retention, according to Figure 24 is at his highest when the RCP 8.5 is considered and at his lowest when using RCP2.6. Overall the scenario with the smallest volume of water retain is MI26 and the one with the highest volume is HR85.

As expected from the observation of the previous graph (Figure 24), the major noticeable difference when looking at the maps (Figure 25) that indicates the volume of retained water per sub-watershed, is the difference between the RCP8.5 and the other two scenarios. Since the value considered is dependent on the area of the sub-watershed, the biggest the sub-watershed is, the largest is the volume of runoff retention.

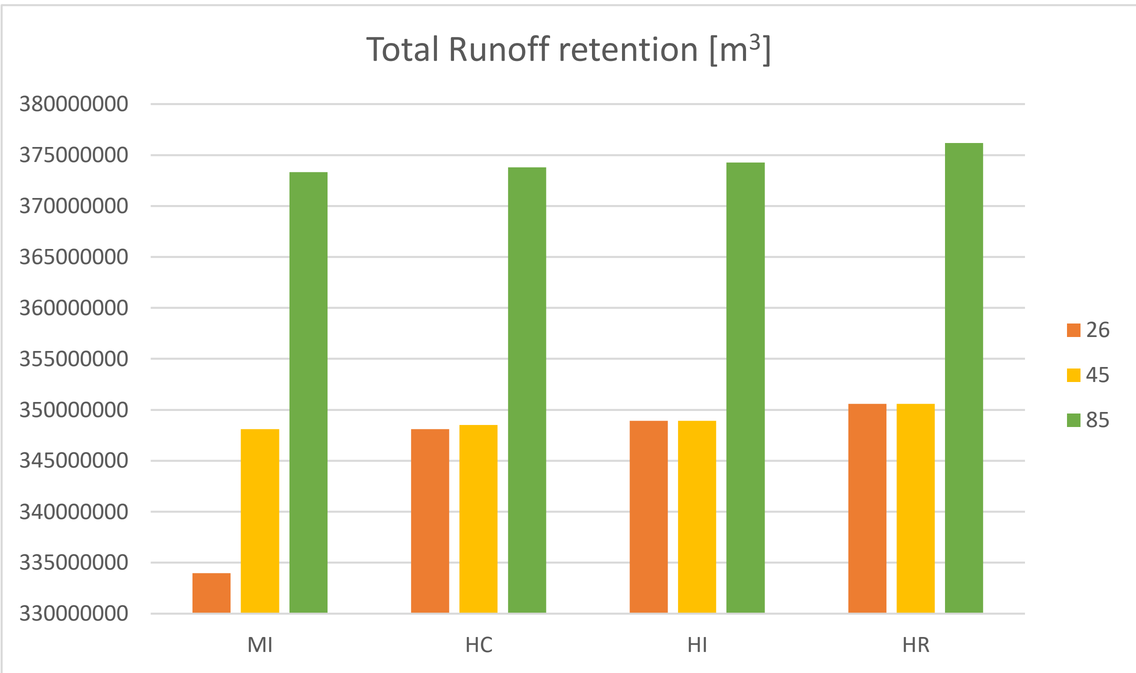
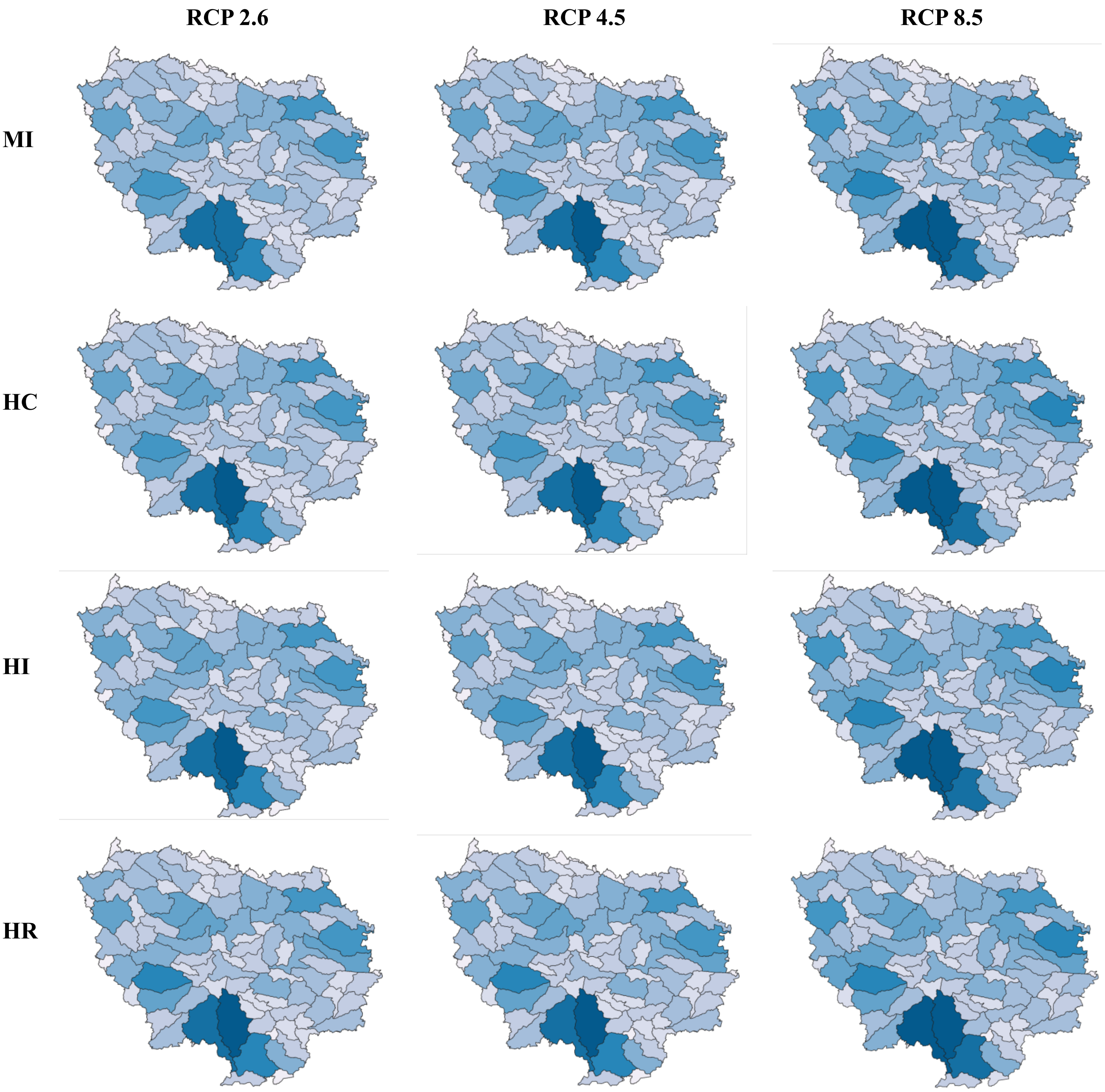


FIGURE 24 Total volume of Runoff retention for twelve possible future scenarios.



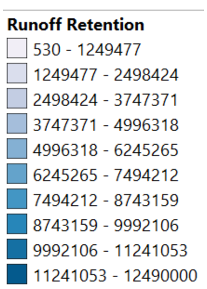


FIGURE 25 Spatially explicit representation of the Runoff retention per sub-watershed, for twelve possible future scenarios.

Urban cooling

Past present and future

To study the urban heat island phenomenon, night and day urban cooling effects were considered separately since different mechanisms work depending on the time of the day considered: while during the day the heat is absorbed and by surfaces and buildings, during the night the same heat is released causing the temperature to increase. It's easy to understand why urban areas, that are built using materials that have a higher capacity of storing heat, and where there is generally less vegetation, are the areas most affected by UHI effect and how the presence of natural element would help mitigating the effect by providing a cooling effect through shade and evapotranspiration.

The indication used is Heat Mitigation Index, calculated as reported in the previous chapter.

Figure 26 shows how the heat mitigation index (daytime) changed in time using the year 2017 as reference. the trend from 1982 until 2017 is overall characterized by a decrease in the cooling capacity showing a variation of the 2.2% from the year 1982. The trends don't change when looking at the HI scenario, where it is foreseen an ulterior decrease of 0.7% of the heat mitigation of the reference year.

Even more interesting are the results found when looking at the night-time scenarios for the heat mitigation index. In this case, all four the future scenarios have been considered and the results clearly show how each future urbanization solution impacts the cooling capacity in a different way. The data collected from 1982 to 2017 show a decreasing trend. The trend is kept also when looking at future projections. It's important to notice that according to the Figure 27, the scenario that uses less land has a higher cooling capacity than the scenarios that use more land for urbanisation purposes. The variation found from 1982 to 2017 amount to the 6.6% while the variation of HMI from the reference year ranges from -0.5% to -3.6%.

The maps showing the daytime heat mitigation index aggregated per neighbourhood or city boundaries are here reported for the years 1982, 2017 and for the scenario HI45 (Figure 28). As expected, the areas most urbanized have a lower HMI while the green areas have higher HMIs. Throughout time an overall slight decrease in the heat mitigation index is noticeable.

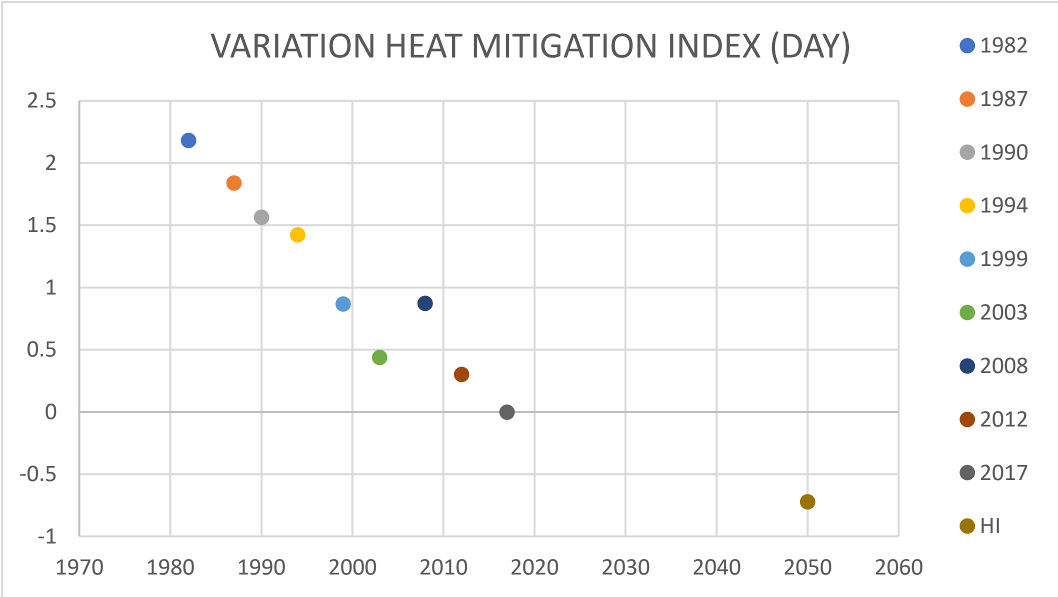


FIGURE 26 Variation from the reference year of the heat mitigation index during daytime for Île-de-France, from 1982 to 2050, scenario HI4.5.

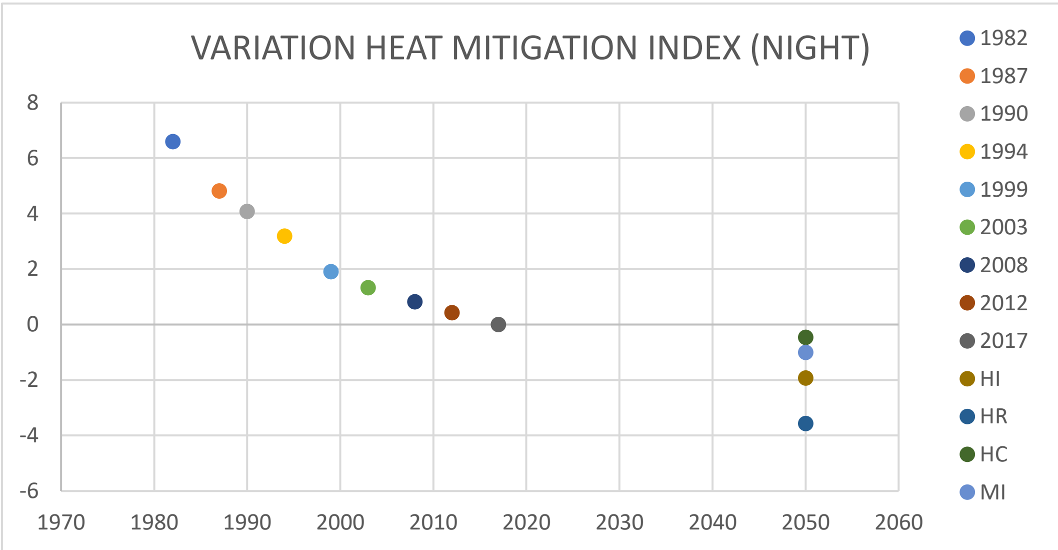


FIGURE 27 Variation from the reference year of the heat mitigation index during nighttime for Île-de-France, from 1982 to 2050, scenario HI4.5.

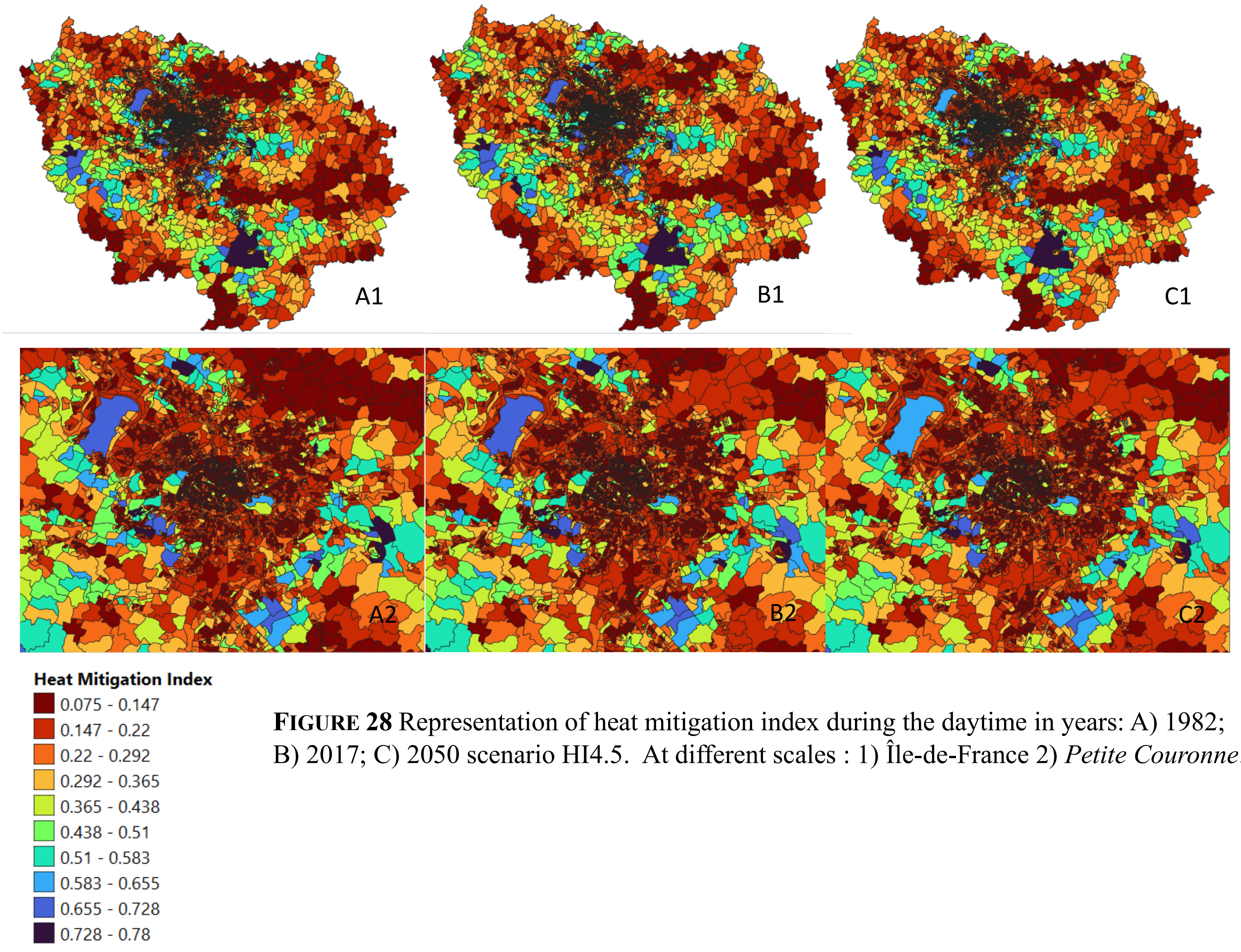


FIGURE 28 Representation of heat mitigation index during the daytime in years: A) 1982; B) 2017; C) 2050 scenario HI4.5. At different scales : 1) Île-de-France 2) *Petite Couronne*.

The maps regarding the nighttime heat mitigation index (Figure 29) offer a clear view of how heat mitigation index is connected to urban sprawling as it's easy to link the growth of the urban area to the areas that in time have a decrease in their cooling capacity. Except for the metropolitan area of Paris and the urban areas nearby, no major changes can be noticed in the region, regarding the HMI, overall the changes are in the direction of decreasing the HMI.

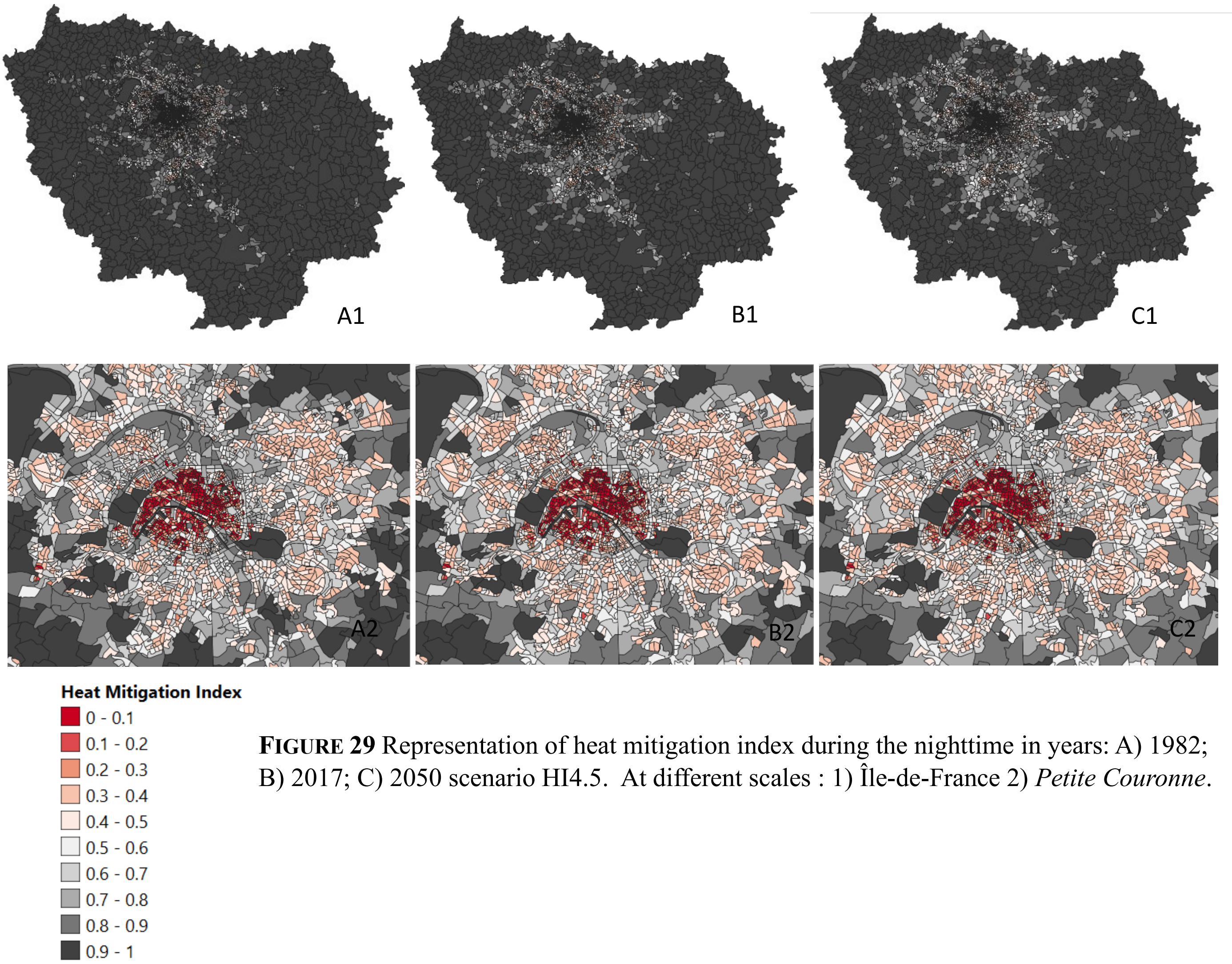


FIGURE 29 Representation of heat mitigation index during the nighttime in years: A) 1982; B) 2017; C) 2050 scenario HI4.5. At different scales : 1) Île-de-France 2) *Petite Couronne*.

Relative importance and combined effect of land use and climate change

The overall Relative importance index for daytime HMI was found to be positive, suggesting that overall land use change has a slightly greater impact on the Urban cooling ecosystem service while the Combined effect index showed no interaction between land use change and climate change. However, with a more detailed look at the aggregated results and the RII and CEI for each neighbourhood or city , it was found that for the 43.6% of the areas land use change was the most important factor of the two, against the 50.7% of the neighbourhoods for which Climate change was relatively more important than LUC, and the remaining 5.7% of the neighbourhoods that didn't show a relative importance for neither of the two factors. CEI at local level showed a perfect distribution between the three options with 33.1% of neighbourhoods suggesting inhibitory combined effect, 33.6% of neighbourhoods showing a synergistic effect and 33.3% of neighbourhoods showing no combined effect whatsoever.

For the nighttime heat mitigation index, the overall relative importance index also showed that land use change is more important than climate change, while for the combined effect a weak synergy between the two factors was found. A more detailed view showed that for the 55.7% of the neighbourhoods, land use change is more important than climate change in the regards of cooling capacity, for the 37.5% climate change was more important and for the remaining 6.8% the two factors had the same importance.

The combined effect index at a sub-regional scale showed that for 39.9% of the neighbourhoods the two factors had an inhibitory effect one to the other, for the 39.5% they had a synergistic effect and for the remaining 20.6% of the neighbourhoods no combined effect was detected.

Comparison of future scenarios: Land Use and Climatic component

The comparison of the twelve possible future scenarios highlights that during the day, the scenarios built using the High demographic growth and rural housing are the ones that keep the highest Heat Mitigation index, while the scenarios built on the premises of high demographic growth and individual housing solutions are the ones that show the lowest HMI (Figure 30). As far as the climate scenarios are concerned, the RCP8.5 scenarios result in the highest HMI while the RCP4.5 scenarios have the lowest HMI.

The night heat mitigation index on the other hand shows different results: the housing solution that results in the biggest decrease in cooling capacity is in fact rural housing while the solution that keeps the highest cooling capacity is the collective housing. For the night heat mitigation index, the distinction of the RCPs doesn't seem to influence the HMI, as can be seen in Figure 31, the values of HMI are comparable. Overall regardless of the scenario considered, the value of the HMI at night is more than double the value during the day.

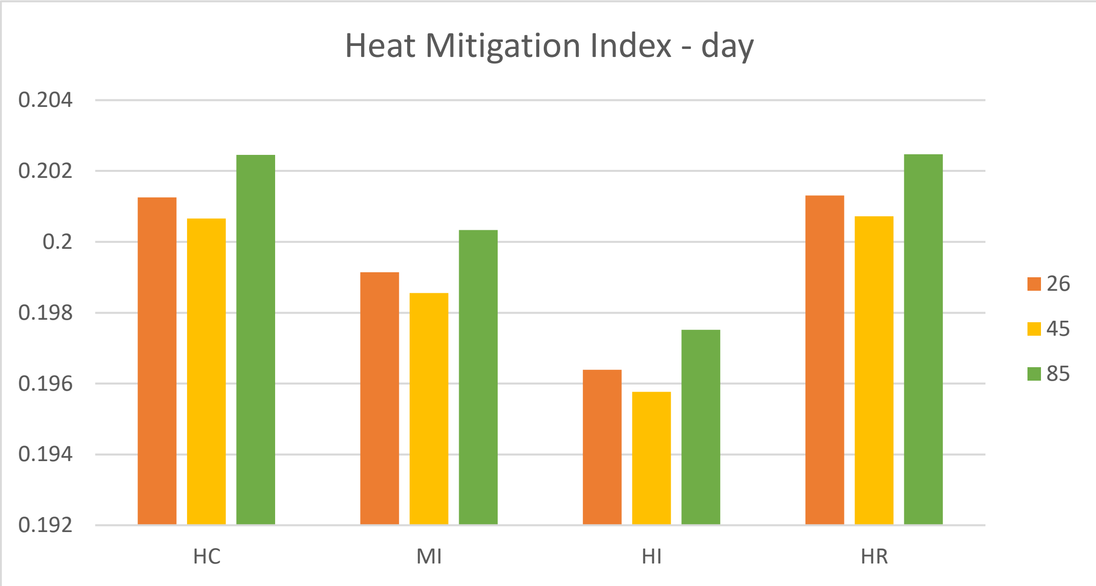


FIGURE 30 Heat mitigation index at daytime for twelve possible future scenarios.

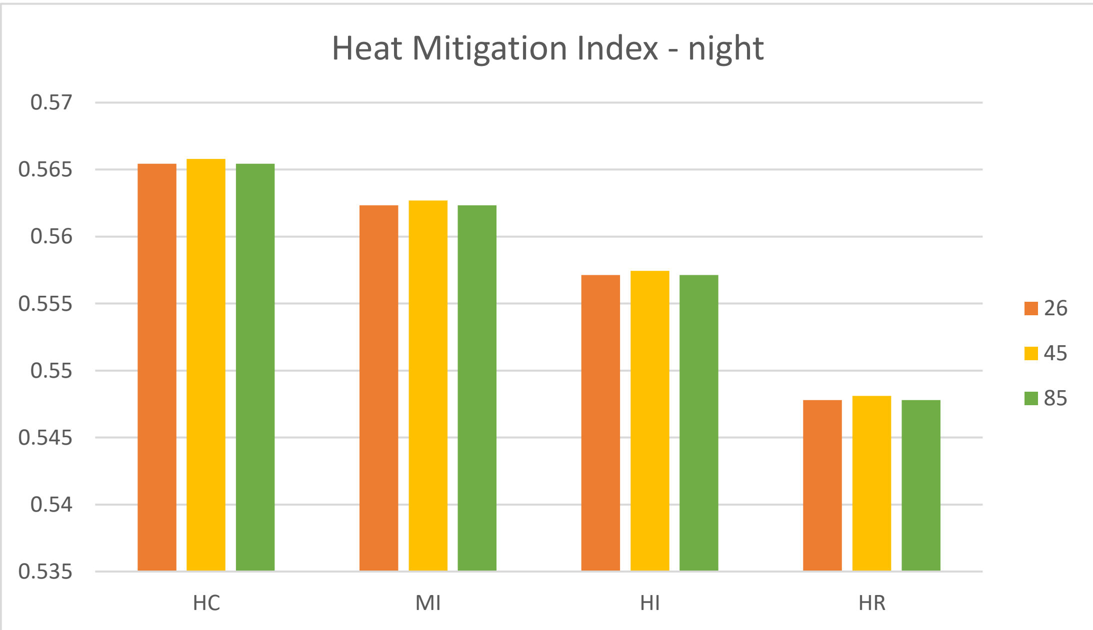


FIGURE 31 Heat mitigation index at nighttime for twelve possible future scenarios.

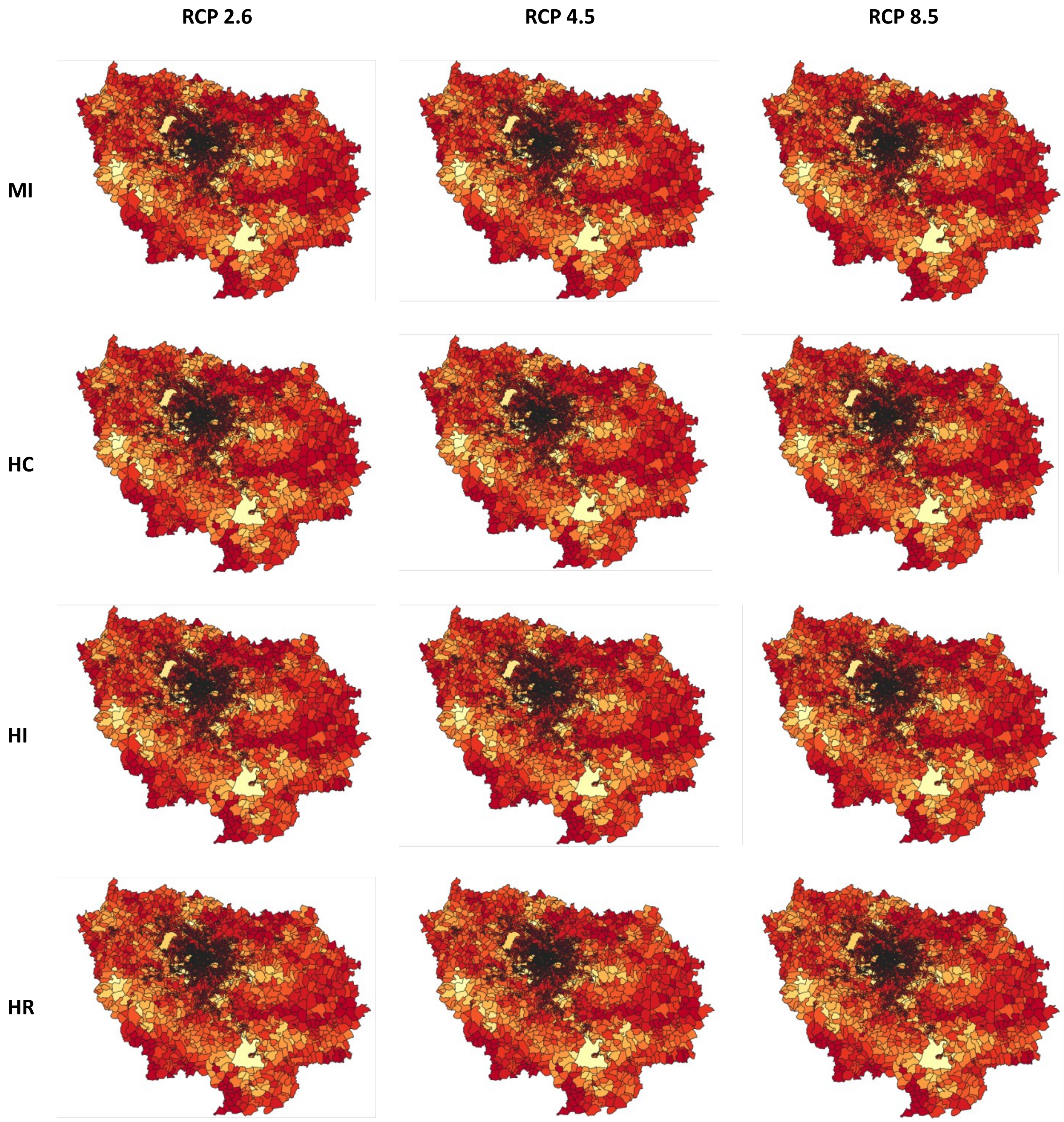


FIGURE 32 Spatially explicit representation of the Heat mitigation index calculated for the daytime, for twelve possible future scenarios.

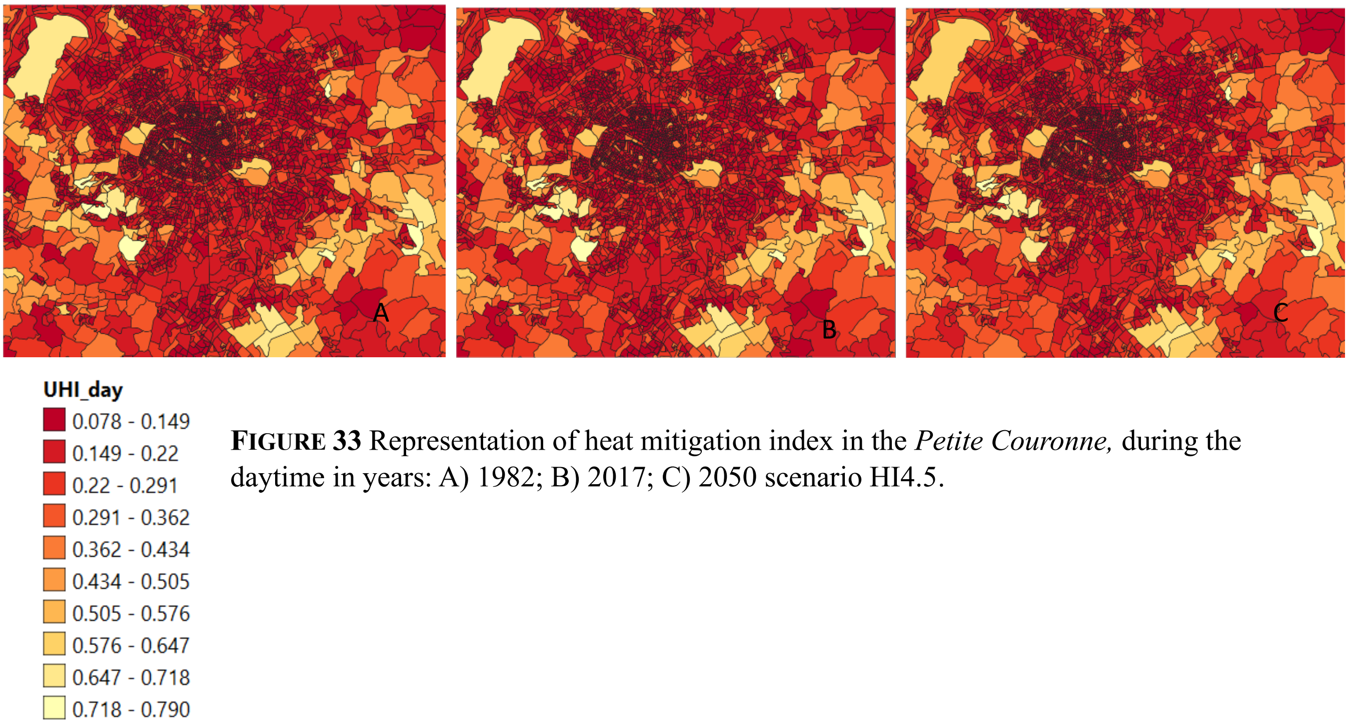


FIGURE 33 Representation of heat mitigation index in the *Petite Couronne,* during the daytime in years: A) 1982; B) 2017; C) 2050 scenario HI4.5.

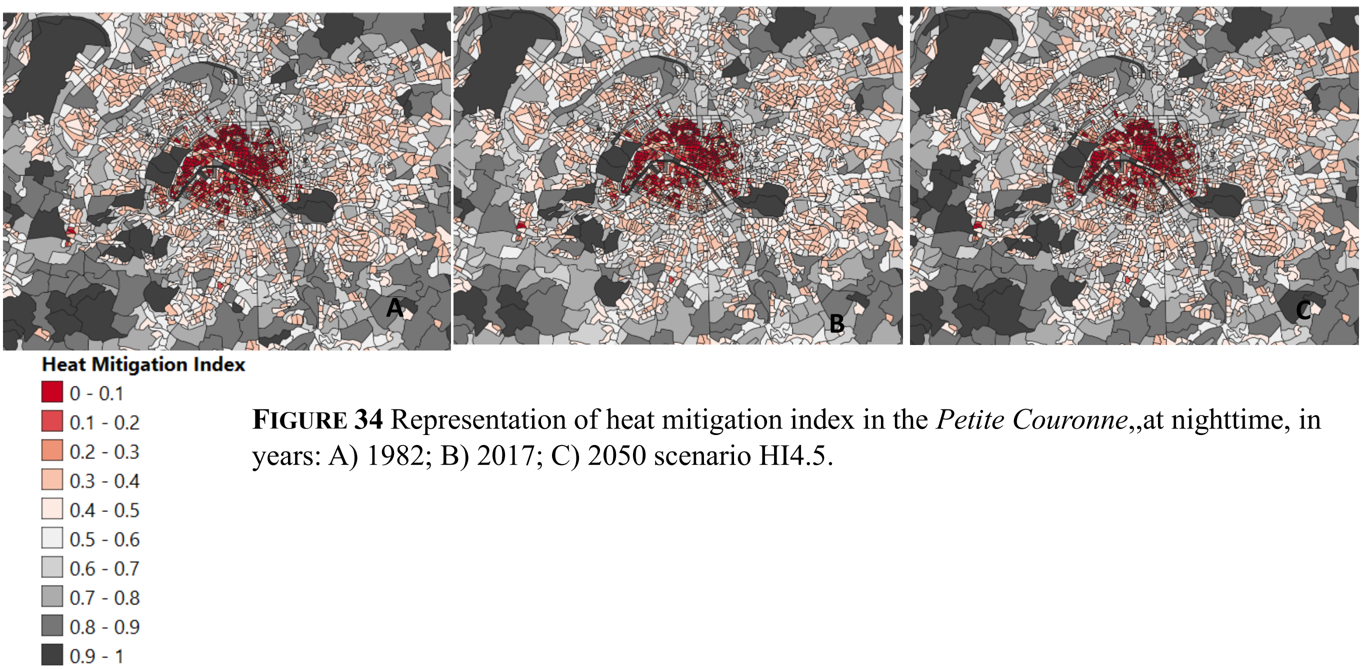


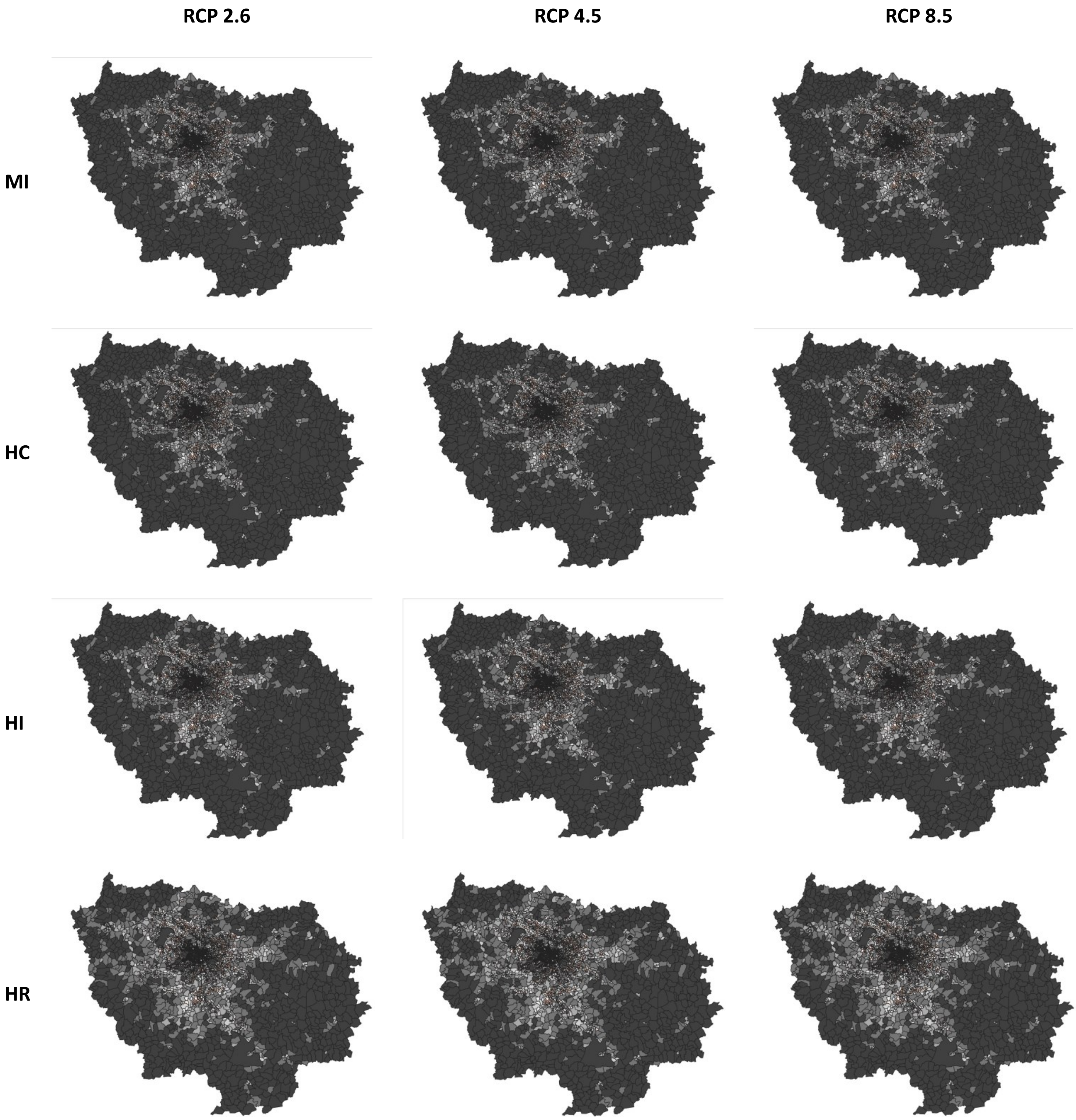
FIGURE 34 Representation of heat mitigation index in the *Petite Couronne*,,at nighttime, in years: A) 1982; B) 2017; C) 2050 scenario HI4.5.

The comparison of the daytime HMI at a zonal level doesn't point out major changes in the HMI from one scenario to another, as predicted, the areas with higher presence of natural elements are the ones with a higher cooling capacity, while the ones characterized by higher urban elements, such as the city of Paris, are the ones with the lowest heat mitigation index (Figure 32).

When looking at the metropolitan area of Paris, (Figure 33) the change that is the most noticeable, is located in the upper left part of the map and corresponds to the *Forêt de Saint-Germain-en-Laye*, a $35m^2$ forest west to Paris, where the HMI decreases when moving from the scenario MI26 to HR85.

Finally the comparison of the cooling capacity at night shows a high dependency on the land use changes from one scenario to the other, highlighting how HR scenarios are in fact decreasing the cooling capacity in the whole area that corresponds to the projected urban sprawl. On the other hand, no major changes in the HMI are noticeable when moving from one RCP to another, inside the same Land use scenario (Figure 35).

A closer look at the city of Paris (Figure 34) doesn't highlight major changes in the city centre and that could be easily associated with the fact that due to the high residence density of the area, no major changes in land use are expected, but rather, the areas that are going to be most affected by the demographic growth are the ones adjacent to the city.



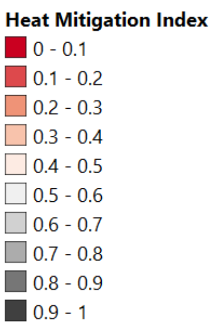


FIGURE 35 Spatially explicit representation of the Heat mitigation index calculated for the nighttime, for twelve possible future scenarios.

DISCUSSION

In the upcoming chapter the results reported in the previous chapter will be discussed focusing on the three main questions that motivated the study: what trends were noticeable when comparing the information on the status of the ecosystem services in the past, with the projection of their future condition; which factor, between Land Use Change and Climate Change was more impactful for each service, and whether there was a detectable cumulative effect between the factors considered; and finally how do the ecosystem services respond to different future scenarios, are the models used robust enough to weight the differences of the twelve scenarios considered into the assessment of the ES's status. Then, some considerations on the strategies to use and the implications of this kind of work have been made and finally, the strengths and weaknesses of the work were illustrated.

Past present and future of ecosystem services

Comparing information between past and future scenarios is not a simple task since the comparison happen between experimental data and projected information that, even if accurate, for their nature cannot be exact. Another important note to make before starting to discuss the results obtained is that, comparatively to the accuracy used in the creation of the future scenarios, the information used to run the models for the past data weren't as accurate. In fact, oftentimes the same data such as precipitation was used during the IDEFESE study as input data for more than one past scenario, thus resulting into outputs that do not consider the possible variation between one year and another, that are due to climate other than land use change. When this note was made to the fellow researchers that had previously worked on the project, it was chosen not to run again all the models with more accurate information for each year and scenario studied, as that would have slowed down the study and as it was believed that the change in land use was already enough to highlight how ecosystem services were affected by land use changes.

While this reasoning was without a doubt right when the focus of their research was only on land use changes and their impacts on ecosystem services, once evaluating the impacts of both climate change and land use change more accurate information on past climatic data should have been used, in order to have a more nitid distinction between the services' status 1982 until 2017. This lack of precision fortunately only affects the first model considered, seasonal water yield, where we can see that the variation between the 9 past scenarios considered, has no relevance whatsoever, when compared with the variation in groundwater recharge found for the four future scenarios considered. The overall decrease in the volume of groundwater recharge is in line with the researchers' expectations, as the substitution of green areas and permeable land covers with urban areas and impermeable land covers logically results in an increase of runoff water (quick flow) to the expenses of the groundwater recharge.

The maps representing the groundwater recharge per sub watershed also highlight a great variability between the reference year (2017) and the scenario preferred as "HI45" , but despite the great variability the areas of the map that had higher values of groundwater recharge in 2017 kept a relatively higher amount of groundwater recharge also in the scenarios representing 2050. It can be drawn from the results obtained that this status of the seasonal water yield ecosystem service in 2050 is projected to be at its worst and largely inferior to its current status.

Nutrient delivery ratio was evaluated using two nutrients: Nitrogen and Phosphorus. As mentioned before the main reason to keep both the new trains as indicators of the ability of this oil to retain no trends is due to the fact that the two nutrients have different preferential paths, in fact Nitrogen is transported via a superficial and a sub superficial flow while Phosphorus is only transported through a superficial flow. As a consequence the hypothesis of the researchers is that the impermeabilization of the soil derived from the urbanisation of the region will affect Nitrogen more than Phosphorus retention. This was in fact confirmed by their results obtained: it is noticeable how for Nitrogen the was a drastic inversion of the trend established from 1982 to 2017, in favour of a lower percentage of retained nutrients. Despite the variation between the reference value and the future scenarios isn't great, it is still bigger than the variation in the past 35 years.

On the other hand Phosphorus retention continued the trend established since 1982, showing the lowest percentage of retention in 2050. It's interesting to notice how the variability inside the four future scenarios considered is relatively high for Phosphorus while for Nitrogen the value of nutrient retention doesn't seem to fluctuate much between the four future scenarios.

There is a high difference between the retention capacity of phosphorus, that reaches the 87% and nitrogen that reaches the 50%: this difference in the percentages is probably due to the different paths and processes the nutrients go through, and to the different ways the models are constructed. Overall it can be stated that throughout the years, the status of the ecosystem service has gone depleting for the Phosphorus retention, while for Nitrogen the projections show an inversion of the trend resulting in less benefits for the people that live in the region.

As previously mentioned, the only parameter that was subjected to a change in order to consider the climatic component in the modelisation of urban flood risk mitigation, was the rainfall depth, which is the depth of rainfall, measured in millimetres, for the design storm of interest. For the period from 1982 - 2017 the rainfall depth considered was the same, and it amounted to 30 mm. As a result no major differences can be noticed when looking at the graph presenting the variation of the water retention over time. Moreover a trend cannot be identified making the researchers unable to link the land use change to the change in their response to a storm event. For the scenario RCP 4.5 the depth of rainfall, the value was 25% more than the baseline value as reported in literature [21]. Overall the variation between future scenarios and the baseline led to an increase of water retention after 16%. This discrepancy between the increase in volume of rainfall and the amount of water retention can be explained by the increase of urban areas that with their impermeable surfaces hinder the full water retention for the storm event.

This inability to discern between the status of the service in the past years suggests that more accuracy is needed when choosing the input data. The fact that the map shows a homogeneous increase in the runoff retention in the whole region, raises a question on the ability of the model to identify the singular characteristics of the sub-watershed since we would expect that the areas characterised by higher levels of urbanisation would have less capacity of retaining water during a storm event, then the areas predominantly characterised by forests and green areas in general.

The urban cooling model shows interesting results on how the indicator (heat mitigation index) varies overtime. Focusing on the daytime it was found that the cooling capacity progressively decreases over time starting in 1982 with a heat mitigation index 2% bigger and finishing in 2050 (scenario HI4.5) with a heat mitigation 0.7% smaller than the reference value. These results go to show that the progressive urban sprawl, has an impact on the ability of the ecosystem to reduce the average temperature causing the environment to be more hostile to the people living in the area and putting citizens at risk of heat related health problems. When reading the maps available, It's interesting to notice that the areas that undergo the most evident change in their hit mitigation index are not the core centre of the cities, that are already saturated with buildings, but rather the surrounding areas that were once characterised by a predominance of green land cover and that's hard now the ones subjected to a change in land cover or land use, due to urbanisation. Other interesting point to note this is that even the green areas that remain untouched bye or bun sprawl such as the forest northwest of Paris, are affected by the change of the surrounding areas resulting in a decrease in their capacity of cooling down the air temperature.

It's even more interesting to look at the maps regarding the night heat mitigation index as they show a distinct separation in the cooling capacity between the areas that are overall considered green areas (parks, rural areas, or forests), and the urban areas. It is also clearly noticeable how the regional heat mitigation index is highly dependent on the land use: in fact the areas that correspond to new developments are the ones in which from one year to the other we have a sharp decrease in the heat mitigation index. Once again, the city centre of Paris is not the area most affected by a decrease in hate mitigation index but rather the surrounding neighbourhoods. The overall variation projected for the year 2050 is in line with what was found from 1982 up until 2017. The maximum variation from 1982 to 2050 is around the 10%, having a variation of 3.6% between the reference year and the most impactful scenario for RCP 4.5.

The results of the urban cooling ecosystem service show that future climatic conditions coupled with urbanisation result in the degradation of the ecosystem service causing a reduction in the residents' wellness.

Land use and climate effect – RII and CEI

Often times in the studies that use InVEST in order to assess the status of ecosystem services and two investigate on the possibilities of future land use development, don't consider the impacts deriving from climate change despite the timescale considered for the possible future scenarios studied, would allow to include it. The use of the two indexes (RII and CEI) serves the purpose of understanding how climate change in land use change interact and whether it is relevant to include climate change into perspective modelling.

For the Seasonal Water Yield ecosystem service the results show that overall climate change has a greater impact then land use change, and that in the large majority of the cases the presence of the two factors results in a synergy. These results confirm the hypothesis that dismissing climate change impacts would result in an underestimation of the effects of a scenario on the ecosystem. The same results were found when studying Nitrogen Retention and Phosphorus Retention where the large majorities of the RII per sub-watershed indicated that climate change is more important than land use change on the ability of the service to provide for people's needs. Overall the cumulative effect suggested that for this service the two factors have a neutral relationship, neither inhibitory nor synergistic. It's interesting to notice in the case of Phosphorus retention that the information on the relative importance seems to be contrasting when the data are aggregated per sub-watershed, compared to when we consider the region as a whole. This apparent contrast suggests that on average on a large scale such as an entire region could have a hindering or smoothing effect that can result into misinterpretation of the actual impacts and consequences of a project. The results coming from the Urban Flood Risk Mitigation model also suggest that climate change is more important than land use change when studying storm events, and the combined effect index suggests that the two factors have a synergistic relationship. Finally the Urban Cooling Model presented a positive RII at a regional level that suggests greater importance for land use change while at a sub-regional scale climate change was more important for the 50.7% of the neighbourhood, suggesting yet again that climate change cannot be overlooked when assessing the impacts of future modifications of the environment, as its impact is as important if not more important than the land use change itself and that it should be taken into consideration as an aggravating factor to the status of the ecosystem services.

Comparison of future scenarios

The comparison of future scenarios was done to understand how sensitive the models were to a range of scenarios that represented many perspectives. This scenario that was considered the most impactful for both the climatic and land use perspective was HR8.5 while the scenarios HC2.6 and MI2.6 where generally considered the ones that represented the best-case scenarios.

For SWY the distinction between the scenarios is clear, showing that the lowest RCP correspond to better conditions for the ecosystem service, while as far as land use is concerned the results seem in contrast with the expectations since the scenarios considered less impactful where the ones with a lower groundwater recharge. Although this result needs further investigation it is reasonable to say that the model is sensitive enough to elaborate on the impacts of a wide range of scenarios.

The Nutrient Delivery Ratio model shows some contrasting results between the sensitivity of the model when calculating phosphorus and its sensitivity when calculating nitrogen's retention, in fact for Phosphorous, the model seems to be able to pick apart the different impacts of the 12 different scenarios, both for the three climatic possibilities and for the for land use possibilities, while for nitrogen it looks like the sensitivity for the climatic possibilities is even higher, while land use scenarios seemed to have no impact on the model's outputs. In the case of Phosphorus retention, as expected, the best-case scenarios results in better ecosystem services conditions while the worst-case scenario for land use has the highest impact on the ability of the ecosystem to offer a proper service. It is interesting to notice that the best conditions for the ES happen with RCP4.5, rather than with RCP2.6 as it would be expected. Nitrogen delivery ratio displays the same behaviour when comparing climate scenarios, but no distinction between the land use scenarios proving that more work is needed for the model to fully grasp the nuances of the possible future scenarios.

The same thing could be said for the Urban Flood Risk Mitigation model, where except for MI2.6, the outputs obtained do not show a noticeable distinction between the different land use conditions, and the scenarios with RCP 2.6 and RCP 4.5 give almost the same outputs. The scenarios created using RCP 8.5 display the highest runoff retention, which appears to be in contrast with what expected, given the initial conditions. In this case, since the model only works using as input one single value for the runoff depth, it was expected that the model wasn't going to be sensible enough to represent the full spectrum of the possible scenarios. It is therefore safe to say that the model needs further attention in order to be reliable when used for perspective modelling.

Finally the results obtained from the urban cooling model, suggest two different conclusions: first, when analysing the daytime urban cooling effect, the model shows a high sensitivity and it's able to distinguish the nuances of the 12 scenarios. The scenarios with RCP 4.5 are the ones that result in lower cooling capacity, while the ones created on RCP 8.5 seem to have the highest heat mitigation index. As far as the land use scenarios are concerned the one that shows there has the degradation of the ecosystem service is HI. Of course the results found are not absolute values, they are rather dependent on the total maximum temperature found in the urban area, and the average temperature in the rural areas, so even if the results show higher HMI for scenarios such as HR8.5, that doesn't mean that overall this scenario is the one with the lowest temperature on average. The second comment to do is on the nighttime urban cooling effect, where it's easy to see that the model doesn't have the ability to discern between the different RCPs used, and the results appear almost the same for the three climate possibilities. For the land use on the other hand there is a clear cut between the four scenarios, and the results confirm what is expected by the model, showing that HC scenarios, that are the scenarios less impactful on the land use change, are the ones that conserve the highest heat mitigation capacity, while the HR scenarios, the most impactful on the land, have the lowest heat mitigation index. In conclusion, despite the model seems to be robust enough for the daytime UC effect and four the land use scenarios in the nighttime model, further investigation is needed in order to understand why no distinction is appreciable when comparing the different climate possibilities.

Strategies and implications

The approaches used in the study have as their main application as support of policymakers. In fact the methodologies presented in the work, are fundamental to provide informed recommendations on environmental investments, environmental policies, and management strategies.

Firstly, a historical representation of the status of the ES is vital to acquire a greater viewpoint on the issue and moreover, to understand how present or future projections are intercepting past trends, to picture how impactful a project can be, not only in the immediate future, but also in the long run. This type of assessment can facilitate the comprehension of the impacts of management strategies and can help realize the direction the ES in consideration has taken over time. If more than one ES are analysed at the same time, the juxtaposition of their historical representations can be of practical help to visualize the greater picture, the overall status of the ecosystem services and to identify possible solutions using as foundation a comprehensive knowledge of the history and the present state of various, interconnected ecosystem services.

Secondly, our work falls into the realm of the Sustainable Development Goals (United Nations, 2015) as studies like the one presented here are the first step in the protection and restoration of terrestrial ecosystems, in the intervention needed to combat climate change and its impacts, and in the shaping of resilient and sustainable cities. Moreover, these approaches facilitate the comprehension of their relationship between lenders change, climate change and their effect on ecosystem services provision, in fact the use of relative importance is useful to identify hot spots of ecosystem services, both for gains and for losses. Local policymakers are in need of assistance on deciding what areas should be protected and where to invest in a way that doesn't negatively affect ecosystem service provision (Bai *et al.*, 2016). In this sense using the relative importance index can be a way to identify the areas where the ES provision is more sensitive to land use change, and opt for tailored solutions (Hoyer and Chang, 2014). Furthermore the use of maps can help identify changes on the ecosystem service provision and maps can be used a space for landscape policies and management decisions, indeed, once the RII is locally calculated, the logical segue would be to have spatially explicit representations of such index, to easily identify hotspots and make trade-off decisions regarding landscape management. Together with RII, CEI can be used to ensure effective provision of ES. Synergistic areas could be identified and left as future protection areas while areas with inhibitory effect can be used for future urban developments, particularly where, according to the RII, Climate Change is more important than Land Use Change.

Finally, the comparison of different future possible scenarios serves two purposes: on one hand it expands the knowledge on possible consequences of land management decisions, it shows best case scenarios and worst-case scenarios, assisting local policy maker with a deeper and more comprehensive understanding of the implications of their actions, vital to have a sustainable development. On the other hand, the combination of four land use possibilities with three climate pathways, is extremely important for researchers and modellers, and its vital when working on perspective modelling as it allows to see where the models used lack in the sensitivity needed, where they can be ameliorated, where further research and development is needed and, more generally, identify until what point InVEST's models are reliable and what are the main limitations of its models. To conclude, the methodologies proposed in this study provide an effective tool identifying trend and implications of changes in land use, for making trade-off decisions to ensure the provision of desired ecosystem services based on the synergistic or inhibitory effects, and to understand models' limitations for more accurate predictions. Policy makers can be better-informed on where to invest, to enhance or restore ecosystem services. Furthermore, it is evidenced from the results that policy implications are scale dependent, and therefore sub regional landscape decision should be accompanied by localized approaches and research, as it was found that results on regional scale differ significantly for results at sub-regional scale. This research framework is applicable in other regions.

Strengths and limitations

The study has some strengths and some limitations that will be summarised here.

The approach used to assess ecosystems services provision in the Paris region, land use change in climate change impacts and the approach used to evaluate invest ability to paint a picture of future scenarios, have old green characterised by their straightforwardness and the fact that they give easy to interpret responses. Invest has the perk of being extremely versatile and fast when considering the number of scenarios and models tested in this work alone. The study can be replicated in other regions, even in areas with less data on land use and climate change such as developing countries. The results found are spatially explicit, therefore easy to interpret for a non-expert audience, the simple representation of the outputs makes the study an accessible tool to explore possible implications of land use and climate change. This study is also one of the few that analyses four ecosystem services at same time, and twelve possible future scenarios using the combination of four climate pathways projections, two demographic growth scenarios, and three residential solutions, for a total of four land development options, expanding the view the complexity of perspective modelling, and land management implications. The relative important index and the cumulative effect index were calculated both at regional and subregional scale, highlighting the differences between the two options, and providing useful information on how LUC and CC interact.

Despite these strengths, this study also has some limitations. The study was carried out using two scales: regional and sub-regional scale. The results differed between the two scales, especially when calculating RII and CEI, showing that despite the convenience of using a regional scale to represent the ES provision, this scale has the potential to leave out important details at a more local level, resulting in less accurate information. Therefore for future research, localized approaches should be applied, to provide more accurate results. Although InVEST models have been described as less accurate than process-based models such as SWAT (Soil and Water Assessment Tool), they have been widely recognized as suitable for multiple-scale ecosystem services assessments (Vigerstol and Aukema, 2011; Lorencová *et al.*, 2016). However, the modelling and data limitations reported on the software documentation (Sharp *et al.*, 2016) and found as result of this study cannot be forgotten and must be considered when working with InVEST or when replicating the entirety of this study or its parts elsewhere.

Future developments

This work is a continuation of the IDEFESE project, and it opens new doors on the investigation of the impacts of climate change in addition to land use change, in the region of Paris, and some ameliorations can be done in the future research. Firstly, a more detailed data collection should be done to have more information of past ES provision and the results could be aggregated at a sub-regional level, perhaps focusing only on the area that is interested by future urban development, and not on the whole Île de France. Secondly maps that visually show the local values of RII and CEI should be created, in order to spatially identify the hotspots for good and bad ecosystem service provision, and areas with synergistic or inhibitory cumulative effects for LUC and CC, in order to strategically project ecosystem enhancement measures in the areas that most need them, protect areas from further degradation, and find the most efficient way to obtain sustainable development. Finally further research should focus on incorporating more ES in the assessment, to have a more comprehensive view of the services' general condition, include in the possible scenarios studied, ES enhancement measures to see what positive impact they would actually have in comparison with current projections, and finally, when possible, include the use of other models, (e.g. SWAT) to further investigate the robustness of the models used.

CONCLUSION

This study offers a comprehensive spatial assessment of four ecosystem services using the InVEST's models and it provides an understanding of the impacts of land use and climate change on ecosystem services in Île de France.

A historical overview of the ecosystem services status provided, together with a Projection of how future scenarios can modify the ecosystem services provision. Overall for the for service is considered, future projections suggest a degradation of the past and current status of the services, due to progressive urbanisation of the region and to the worsening of climate conditions.

The relative importance of land use and climate change in the determination of shifts ecosystem services was studied. The results showed that at the sub regional scale, climate change has a greater impact than land use change for all four services, indicating that climate change contributions cannot be underestimated or overlooked when evaluating future ecosystem services conditions. The combined effect off land use and climate change was calculated for the four services and the result showed mostly synergistic effect on groundwater recharge and on runoff retention, while there was a neutral effect on nutrients retention on urban heat mitigation. This information can be useful to localize the areas that should be protected and preserved from land use change, as the areas that are characterised by a synergy between land use and climate change, while the areas with an inhibitory effect, should be the one preferable for land use change, as they are the ones that will be less impacted by the two factors overall.

The comparison of the twelve possible future scenarios highlighted, on one hand how strongly the severity of climate change can affect the provision of ecosystem services for the inhabitants of the Paris region, and on the other hand it showed how in some cases, although overall the models are robust enough to give a clear idea after consequences of land use and climate change, more work still needs to be put into the betterment of InVEST models, before they will be able to fully reach the sensitivity needed to properly discern between the range of possible scenarios.

Despite the limitation of the study, the results found have practical applications, and can be used to support landscape planning with ecosystem service information, the aim of developing more effective ecosystem protection strategies. Climate change appears to be undeniably important in the shifts of ecosystem services provision and according to the results found in this work it cannot be dismissed or neglected. Historical scenarios analysis together with the use of indexes for relative importance and cumulative effects, can be used as simple and straightforward ways to seize the impacts of driving factors such as land use change and climate change on ecosystem services. These tools are important to better understand the mechanisms that link ecosystem services and the two abovementioned factors and are beneficial for assisting policymakers in the creation of more effective and site-specific management choices. The research can be replicated in other areas and expanded through the integration of other ecosystem services' models into the assessment.

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