OPPORTUNITIES FOR GREEN INFRASTRUCTURE TO OPTIMIZE THE URBAN METABOLISM OF RESOURCES

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Introduction

Green infrastructures (GI) have a great potential for improving the lives of city dwellers by improving air quality, reducing the effects of heatwaves, providing natural spaces for recreation and promoting food production, and embrace projects as diverse as urban and peri-urban agriculture, vertical farming, urban forests, green rooftops, parks and gardens, and green corridors. Although these various forms of GI help to make cities more resilient and self-sufficient, we still need to ensure that their implementation is not counter-productive due to a rise in unsustainable uses of energy and water. Fortunately, there are many ways in which GIs can promote a more circular use of resources, especially in urban and peri-urban agriculture (hereafter referred to jointly as UA). In the field of Industrial Ecology, how a city receives, uses and disposes of its resources is known as Urban Metabolism (UM) and is defined as the sum of all the technical and socio-economic processes associated with the production and consumption of key resources (e.g. water, food and energy) that sustain the growth and maintenance of cities (Kennedy, at al 2007). The calculation of UM is a useful way of understanding how a city consumes resources and is both scientifically sound (i.e. it is based on the law of energy and mass conservation) and relevant to urban planners and dwellers alike, and as such it is a precise accounting tool for understanding efficiency, waste and dissipative uses.

The metabolism of a city can become more efficient and require fewer external resources by adopting recycling and recovery methods in what has recently become known as the “circular economy” approach. In terms of UA (see Fig. 1), the adopting of a more cyclical use of resources within cities translates into the recovery of nutrients for fertilizing crops and wastewater and rain water for irrigation. Figure 1

Figure 1. Conventional agriculture is characterized by a linear system whereby resources are extracted and eventually disposed of in the environment, thereby causing eutrophication and resource depletion. A more circular urban agricultural system minimizes external resource use through the recovery and management of valuable resources such as waste and wastewater from other urban systems.

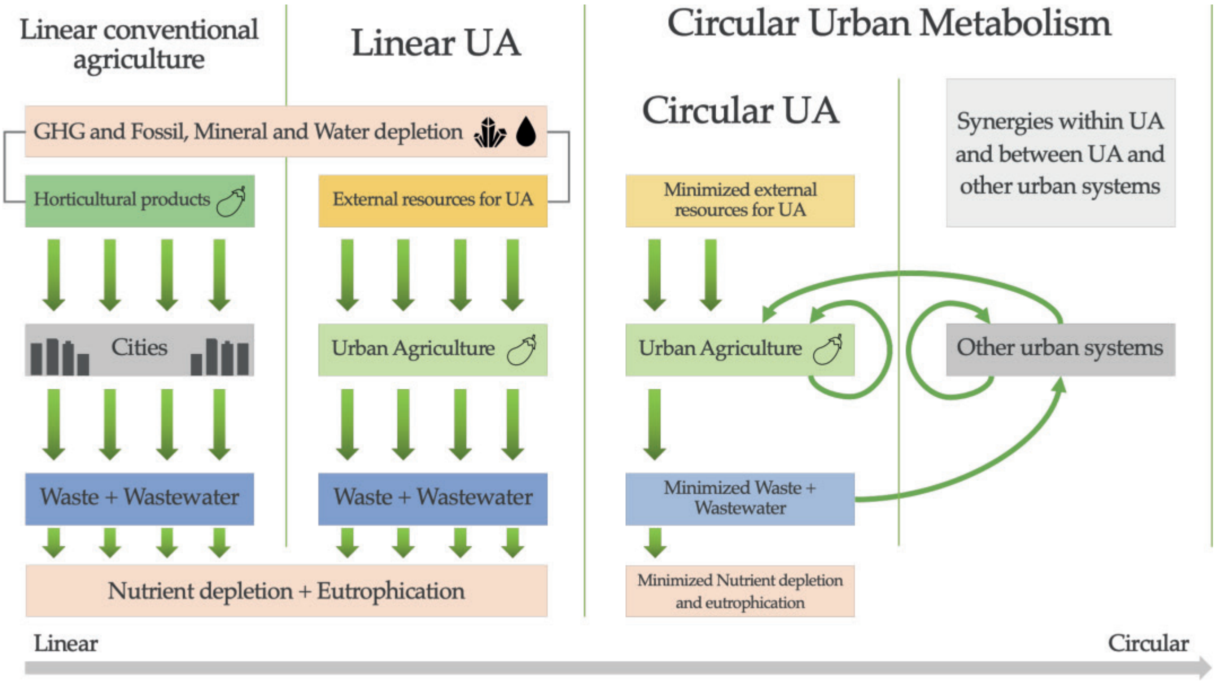
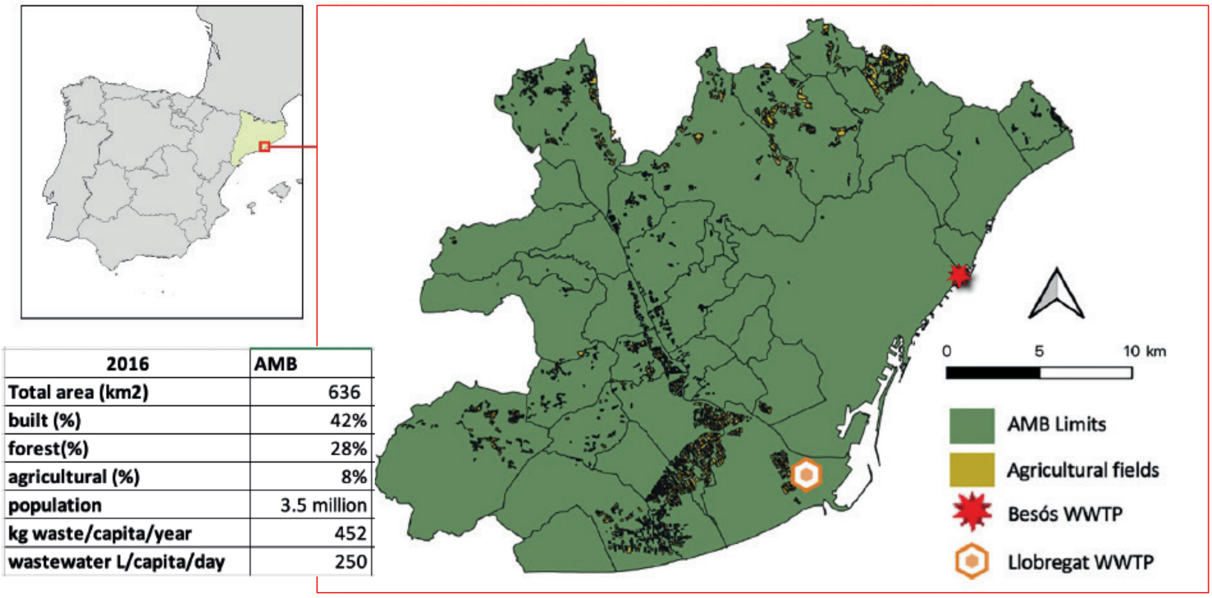


Figure 2. The Barcelona Metropolitan Area covers 636 km^2 and is located in the Catalan Autonomous Community (Spain). The figure also shows the location of the region's main wastewater treatment plants (WWTP) and agricultural areas.



2016	AMB
Total area (km2)	636
built (%)	42%
forest(%)	28%
agricultural (%)	8%
population	3.5 million
kg waste/capita/year	452
wastewater L/capita/day	250

shows how a reduction in the use of virgin resources as a result of recovery loops in urban areas lessens the environmental impact of resource extraction and waste disposal. Urban wastewater and solid waste are huge sources of phosphates and nitrogen that are readily available for plant uptake. In many cities, rainwater harvesting, which does not require energy-intensive treatment, can act as a substitute for a significant amount of irrigation water.

The following sections explore how various UA strategies can improve urban metabolism using the Barcelona Metropolitan Area (AMB) as a case study (Fig. 2). Figure 2 also includes a table summarizing the most important land uses and urban metabolism indicators in the AMB.

Which nutrient recovery techniques are most environmentally friendly in urban systems?

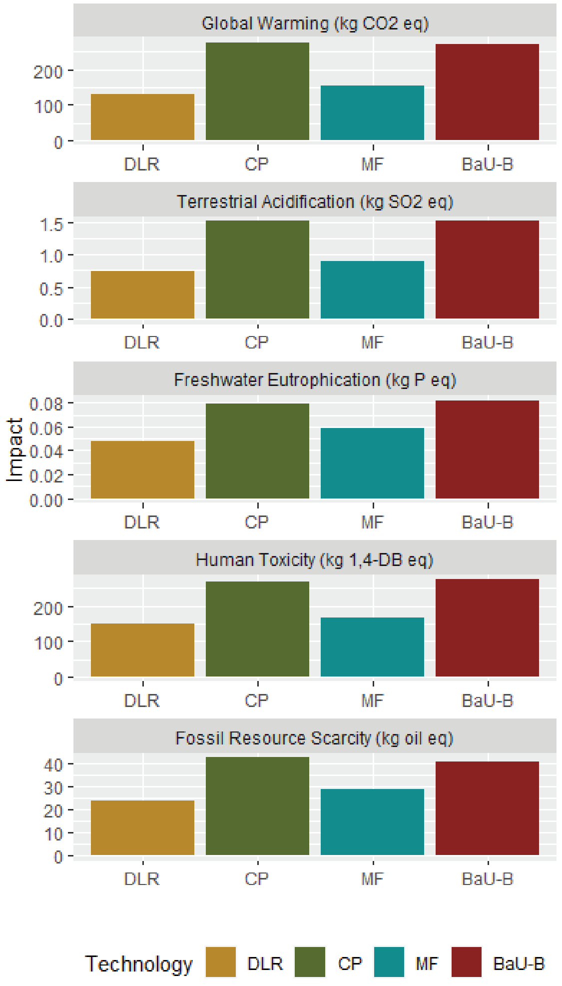
Hydroponics is an attractive alternative to conventional soil-based agriculture in urban systems because urban soil often contains heavy metals and other contaminants. These soil-less systems also allow for more precise water and nutrient management because their porosity and humidity, amongst other factors, are stable and known. Nutrient management is especially important because enhancing nutrient recovery in urban agriculture helps close material cycles and reduce eutrophication and resource depletion (Boneta et al., 2019; Sanjuan-Delmás et al., 2018). Since 2014, the European Union recognizes P as a critical resource (European Commission, 2014), and encourages P recovery from local sources by enforcing a shift towards a more circular use of nutrients.

To explore various nutrient recovery options, we study here how three recovery processes – namely, direct leachate recirculation (DLR), chemical precipitation (CP) and membrane filtration (MF) – can be used to recover phosphorus, magnesium, potassium and calcium from the leachates of hydroponic tomato production for re-use in the same hydroponic urban agricultural system. Tomatoes (type *Lycopersicon esculentum*) were grown from 12 January to 18 July 2017 (a total of 187 days). Harvesting began in the second week of April in the 125-m^2 integrated rooftop greenhouse (i-RTG) of the ICTA building on the campus of the Autonomous University of Barcelona.

As its name implies, DLR is simply a partially closed water and nutrient system in which leachates are re-introduced into the irrigation system, thereby reducing the amount of fresh water and chemical fertilizer needed. Although several different CP technologies exist, we chose the Crystalactor® technology from DHV (Royal Haskoning DHV, 2019) because it is applicable to a wide range of water systems, including those that are suitable for small production systems in urban hydroponics. The reaction involves the precipitation of struvite (also known as MAP or magnesium-ammonium-phosphate) by reacting calcium, magnesium or potassium salts in the wastewater containing soluble ammonium and phosphate compounds (Piekema and Giesen, 2001). The MB technology selected was the microfiltration of wastewater followed by reverse osmosis to concentrate recovered nutrients (MRWA, 2009; Stoughton et al., 2013). The Life Cycle Assessment (LCA), explained in more detail in Rufí-Salís et al. (2020a), describes all the infrastructure, electricity, chemicals and transport required by each technology for recovering the 450 g of P that were leached during the experiment, which ended up producing approximately one tonne of tomatoes.

We applied Life Cycle Analysis (LCA) methodology to evaluate the environmental impact of meeting the nutrient demands of the tomato crop cycle of (i) each of the three nutrient recovery technologies and (ii) the business-as-usual (BAU) scenario of no recovery, which involves discharging leachates into the environment after wastewater treatment (as occurs cur-

Figure 3. Absolute life cycle environmental impacts of four different techniques: direct leachate recirculation (DLR), chemical precipitation (CP), membrane filtration (MF) and business-as-usual (BAU). The impacts are calculated for the functional unit equivalent to satisfying the nutrient demands of the tomato crop cycle under study.



rently in the AMB). BAU consists of the production of mineral fertilizer with the same content of P as that recovered by the three technologies, and includes the impacts associated with discharging the same amount of fertilizer into the environment. The results of the LCA (summarized in Figure 2) show that the three technologies perform better than the BAU scenario, in particular in terms of their eutrophication potential.

Direct leachate recirculation (DLR) technology has the least impact of all the categories, which is mostly due to the small amount of electricity required for the pump and ultraviolet lamp. Furthermore, and just as importantly, DLR is less resource-intensive – because it does not require any chemicals to be used – and the recovery of nutrients reduces the potential for eutrophication. The need for energy-intensive chemicals in the CP technology, which gives similar results to the BAU, counteracts the benefits of reducing the extraction of mineral fertilizers. To conclude, direct leachate recirculation results in the best environmental performance and its use could potentially reduce by half the impact of fertilizing urban agriculture.

Can wastewater feed cities?

The recovery of phosphates (P) from wastewater in the form of struvite is an attractive solution for urban areas given the growing popularity of local crop production and the treatment of large volumes of wastewater in centralized treatment plants (WWTPs). To explore this possibility, we analyzed the potential P recovery and the life cycle environmental impact of integrating three recovery technologies, namely, REM-NUT®, Ostara® and AirPrex®, into the two main wastewater treatment plants in the AMB as a means of satisfying the annual P demand (36.5 tonnes) of urban and peri-urban agriculture in the region. All three technologies recover P in the form of struvite through chemical precipitation (see above), with varying degrees of efficiency and chemical and energy requirements. The LCA methodology is applied here and compared to the business-as-usual scenario of no nutrient recovery.

The system analyzed is depicted in Figure 4. The overall impact of all the AMB's urban sewer system and its crop production and subsequent consumption go beyond the scope of our study. Otherwise, all life cycle stages were contemplated, including the extraction, production and transport of all resources, the WWTPs (both infrastructure and operation) including the struvite recovery processes, the production of mineral fertilizer, and the transport of nutrients to agricultural areas. The data sources are given in Rufí-Salís, et al. (2020b).

Our results show that all technologies are able to recover between 5 and 30 times the amount of phosphates required to fertilize the whole AMB agricultural area annually, even if only one WWTP is operative. This is a truly positive finding as it makes it feasible to expand UA production, thereby ensuring that the AMB can become more independent in terms of food production. Moreover, because the requirements are met by each individual WWTP, it would be feasible to just modify one of them to avoid the environmental impact derived from the upgrade of the WWTP configuration. The Llobregat WWTP would be the most appropriate for nutrient recovery for UA since it possesses EBPR nitrification/denitrification modules and so would cause the least impact in terms of new infrastructure.

In terms of the LCA results, the Besòs always exerts a greater impact than the Llobregat (Fig. 5), mainly due to the fact that the Besòs annually treats more wastewater (125 million m^3) than the Llobregat (94 million m^3). However, the Besòs would require the building of new infrastructures – which the Llobregat facility already has in place – to facilitate the struvite recovery processes. On the other hand, freshwater and marine eutrophication savings in the Besòs are significant improvements due to the ammonium extraction by struvite in the crystallization process and the installation of a nitrification-denitrification process. We believe thus that both Ostara® and AirPrex® are feasible technologies under scenarios of global warming, ecotoxicity and cumulative energy demand, whereas the REM-NUT® alternative is the most suitable for reducing eutrophication.

Figure 4. LCA System definition aiming to determine the environmental impact of nutrient recovery for mineral fertilizer substitution in the AMB.

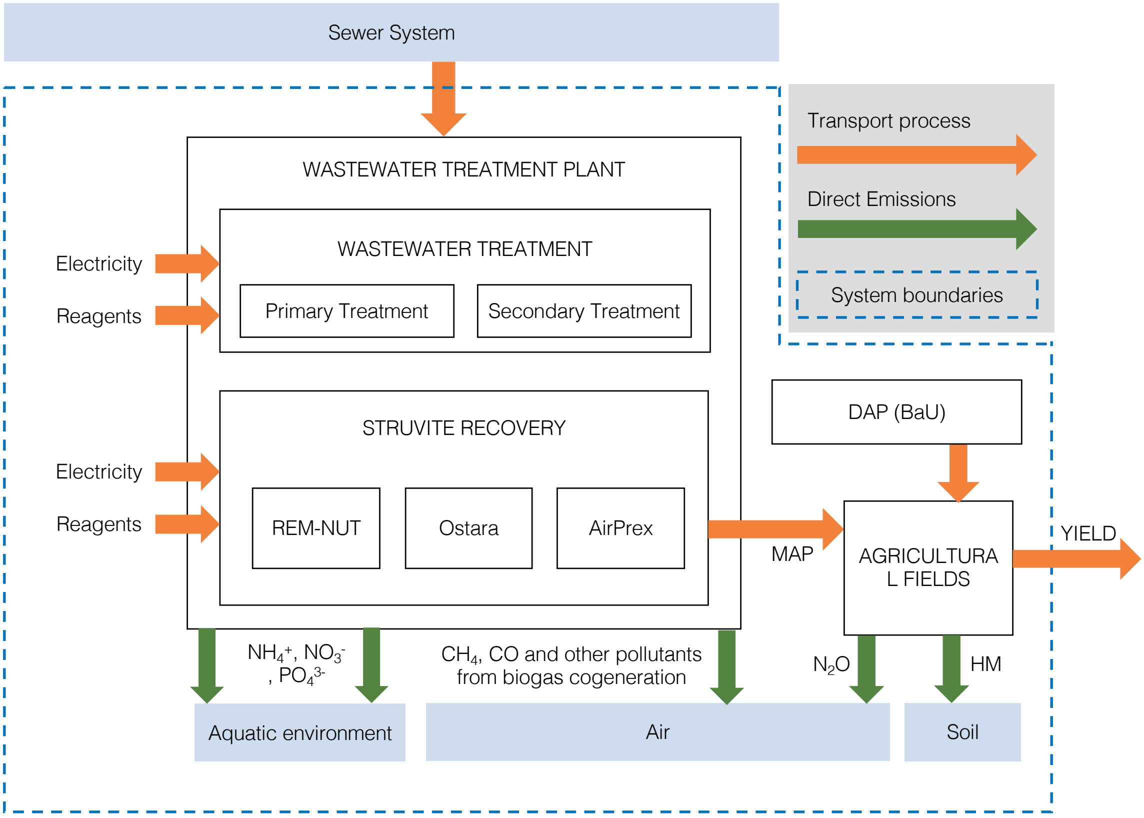
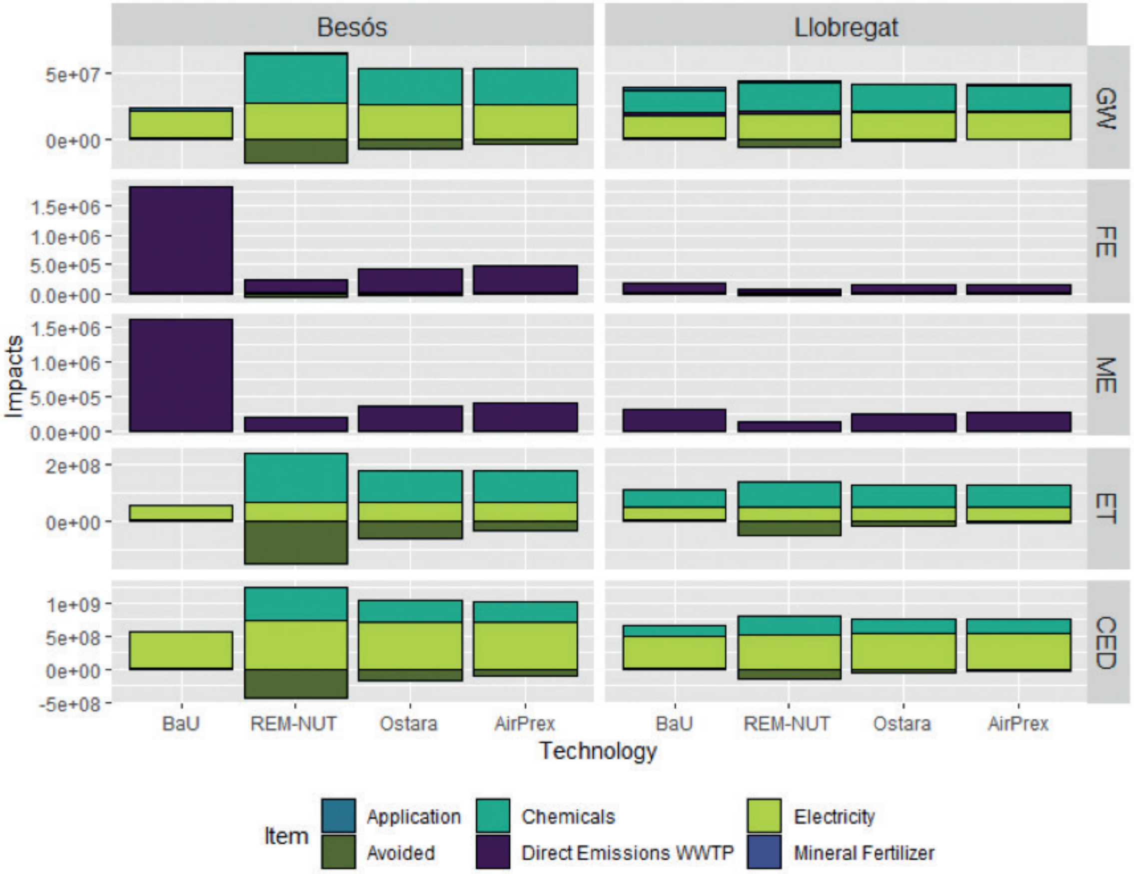


Figure 5. Absolute life cycle environmental impacts of satisfying the phosphate demand of urban and peri-urban agriculture in the AMB under the business-as-usual (BAU) scenario and using three nutrient recovery technologies based on struvite precipitation: REMNUT, Ostara and AirPex.



Conclusions

We explored nutrient recovery at two levels as a means of promoting circular resource use in urban areas: 1) the recovery of nutrients from leachates in an urban agriculture system to improve the efficiency of food production, and 2) the recovery of nutrients from the wastewater of an entire metropolitan area to quantify the potential for avoiding using mineral fertilizers for local food production. For (1), we found that the direct leachate recirculation technology reduces global warming potential, eutrophication and fossil resource use by more than half compared to the business-as-usual linear fertilization methods. Study (2) estimates that the nutrient recovery from the wastewater treatment plants is up to ten times greater than the fertilizer demand from urban and peri-urban agriculture and thus provides ample opportunities for its expansion in terms of resources. Both strategies cut fossil fuel use by reducing transportation and mineral fertilizer production. These are just two examples of the large range of possibilities for creating synergies between UA and other urban systems that in the future can help make cities more resilient and self-sufficient in terms of food production.

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