# *Conceptual Advancement of Socio-Ecological Modelling of Ecosystem Services for Re-evaluating Brownfield Land*

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## Abstract:
Essential environmental resources are rapidly exploited globally, while social-ecological systems at different scales fail to meet sustainable development challenges. Ecosystem services research, which at present predominantly utilizes static modelling approaches, needs better integration with socio-economic dynamics in order to assist a scientific approach to sustainability. This article focuses on Brownfield lands, a unique landscape that is undergoing transformations and provides ecosystem services that remain, at this point in time, mostly unrecognized in public discourse. We discuss the main issues associated with current modelling and valuation approaches and formulate an ecosystem-based integrated redevelopment workflow applied to the assessment of Brownfield redevelopment options.

# 1. Introduction

Ecosystem services (ES) have acquired increasing attention in public discourse over the last 20 years and are today broadly understood through the lenses of well-established classification frameworks, e.g. the Millennium ecosystem Assessment (2005). Derived conceptual models and mapping methods have improved environmental accounting and started to scratch the surface of a complex research field that feeds on an interdisciplinary research landscape (Haddad et al., 2017, Mota-López et al., 2018, Brudvig et al., 2017). However, their role in practical decision making - either by governments or businesses - has progressed little despite such advancements.

Since the Millennium ecosystem Assessment (2005) and the first classification of ES, the field has grown considerably, including the development of capabilities for decision support. Decision support protocols were developed and applied which include a recognition of intermediate services, phases and benefits (Fisher et al., 2009). Focus was then broadened to include sustainability-oriented approaches for the governance of natural resource management, with consideration of multiple systems and agents within systems (Ostrom, 2009). These conceptual frameworks aimed to determine the behaviour of environmental change on ES. For example, several frameworks for ES provision were developed with social-ecological systems (SES) in mind, focusing on the combination of human and natural factors affecting human well-being (Reyers et al., 2013). Others emphasized the response of human societies, integrated within social-ecological systems, by means of an enhanced driver-pressure-state-impact-response (DPSIR) framework (Rounsevell et al., 2010b, Nassl and Löffler, 2015), capturing the feedbacks of anthropogenic environmental changes to the ecosystems' capacity.

The need to strike a balance between the provision of multiple environmental goods and services and the demand of a rapidly growing society led to the introduction of supply and demand scenarios, considering ecosystem integrity and their contributions and health effects on humanity (Burkhard et al., 2012). Conceptual frameworks for analysing ES delivery included potential capacity and flows as well as the role of social preferences (Villamagna et al., 2013). Higher-level conceptual frameworks posed more emphasis on sustainability at the global scale, illustrating distant interactions, i.e. teleconnections (Seto et al., 2012), including the role of trade (Liu et al., 2013, Rockstrom et al., 2009). Recent methodologies for adaptable and robust ES assessment highlight the need for data and model integration (Villa et al., 2014) for capturing the whole complexity that characterizes ES.

In this paper we propose an operational, integrated nature-society-economy workflow for Brownfield land redevelopment and prioritisation. Brownfield land systems, where land was previously used for industrial purposes, are an interesting case to discuss because of their complex interactions with ES. Furthermore, Brownfield land has unique features and large variability that benefit from an integrated nature-society-economy approach: it is a type of land that is constantly undergoing dynamic transformations, impacting on the provision of ES. Such services are in fact imperceptible to the public, hidden behind the overwhelming negative visual impact of many Brownfield land sites. Therefore, successful integration between stakeholder beliefs and recommendations requires new methods that can capture their thoughts and prioritise which ES would be appropriately beneficial to Brownfield land and to the local community. Section 2 illustrates the authors' perceived main challenges of the modelling and evaluation of ES. Section 3 conceptualises the problem of Brownfield redevelopment under the ES perspective and Section 4 introduces an integrated redevelopment workflow detailing how to prioritise ES depending on the original function and location of Brownfield land.

## *2. Current challenges in modelling and valuing ecosystem services*

### 2.1 Current limitations of ecosystem services modelling

ES have gained increased visibility especially from a socio-economic standpoint: the quantification of such services adds valuable information for the selection and evaluation decisions concerning the planning of certain categories of land, such as Brownfields.

Two main limitations associated with the assessment and quantification of ES relate to the understanding and modelling of 1) the capacity of different ecosystems to provide a bundle of varied services, and 2) the unpredictability of tipping points in service delivery. These are affected by both ecosystem dynamics and human activities such as overexploitation and/or the rise of new technologies, as is the case of increased input contribution into agricultural production (Lippe et al., 2011). Both phenomena are characterized by high complexity and deep uncertainty (Hannart et al., 2013) and their study should involve multidisciplinary and transdisciplinary science and technology (Chen et al., 2017). At the same time, they should involve an exploratory modelling approach that can make use of different models (of the same service) in order to capture uncertainties, as done for example in weather forecast practice (Krishnamurti et al., 1999), or in climate change sciences, which uses model ensembles. Therefore, the developing and modelling of future scenarios and trade-off analyses should also be part of the assessment.

### 2.2 Ecosystem services inter-linkages and trade-offs

A variety of challenges limit the effectiveness of ES modelling approaches. In particular, disciplinary boundaries hamper a full study of the effects of human behaviour on ecosystems. For example, theories and models should represent the behaviour of humans in relation to nature, in order to predict adaptive and flexible responses to changes to the environment. Conceptual models currently exist outside the ES domain which can better cater for such non-linear decision making, such as Ostrom's (2009) social-ecological systems model. Various human-based entities, such as organisations and small companies, must be included as part of a theory of evidence which constitutes the perceptions of all stakeholders involved in prioritising ES multi-functionality within certain contexts of land use and cover change (Berbés-Blázquez et al., 2016).

Much interest has focused on the implementation of indicators to assess the status of biodiversity and key ecosystem functions from local to global scales (European Commission et al., 2012, Singh et al., 2006, Steffen et al., 2015, Kumar, 2010, Cotter et al., 2017). However, assessing human impacts on the structural integrity of ecosystems (as well as the other way around), their capacity to supply services, their vulnerability and resilience, remains a challenge. So far, consensus is lacking on the methodological tool(s) used to incorporate inter- and intra-relationships and feedback across the many causal paths and links between nexuses (see Liu et al., 2015). This renders a definition of priorities to support policies at different scales difficult. To this end, scientists have been working on the development of integrated modelling tools to assess the contribution of ecosystems to human activities (see Bagstad, (2013) for a review). In the case of commodity productions, we refer to system dynamics, such as the global unified meta-model of the biosphere (Boumans et al., 2002), later advanced by (Arbault et al., 2014) and then proposed to build a dynamic approach to value ES with the multi-scale integrated model of ES (MIMES: (Boumans et al., 2015)). However, most of Earth system dynamics modelling tools are very coarse in their capability to represent human decision making and thus very far away from representing fine-grained social dynamics. A more effective framework, in this sense, can be based on the combination of agent-based modelling, Bayesian belief networks and opinion dynamics models (Sun and Müller, 2013). Agent-based models are suited to represented complex systems, and in particular, the heterogeneity of their components, the dynamic interactions among them, and the emergence of organizational structures (Balbi and Giupponi, 2010). Bayesian belief networks help in describing the human decision making process by exploring conditional probabilities of cascades of actions or events. Such models — empowered by opinion dynamics models to explain social influence — are used to simulate the actions enabled by decisions, and thereby improve the understanding of socio-ecological systems.

The simultaneous modelling of multiple ES is also a challenge (Bennett et al., 2009) and remains a rather unaddressed topic in the literature (Nemec and Raudsepp-Hearne, 2013), due to data limitations, complexity of the phenomena and methodological gaps (Mach et al., 2015). Services are frequently interwoven and incentives boosting the valorisation of one service may adversely impact other services (Foley et al., 2005, Kinzig et al., 2011). Some recent studies have investigated commonalities and trade-offs among ES (Gonzalez-Redin et al., 2016, Jia et al., 2014, Jopke et al., 2015, Kirchner et al., 2015, Qiu and Turner, 2013, Ruijs et al., 2013, Van der Biest et al., 2014, Balbi et al., 2015, Lee and Lautenbach, 2016, Turner et al., 2014) but the quantification of their interlinkages and the formulation of an explicit functional relationship have not yet been fully achieved. It may in fact be necessary to prioritise a small subset of ecosystems to one specific piece of land as opposed to attempt to squeeze all ES into a single space (Watts et al., 2009, Gómez-Baggethun and Barton, 2013). This procedure of evaluation and prioritisation, already tested for the planning of protected areas using tools such as

Marxan (Watts et al., 2009, Ball et al., 2009) will allow special types of areas to be developed. These areas can then be given an identity and a sense of purpose, questioning the objectives of local development and ES valorisation so that the public can acknowledge what is trying to be achieved not only within the area of the city/landscape but also within more natural environments that are customised for a specific purpose.

The analysis of interlinkages between spatial scales is another issue which is almost neglected by current methodological frameworks, with some exceptions. For example, the LUMOCAP Policy Support System has 4 spatial scales (EU, national, regional, local) with flows from one to the other (top-down as well as bottom-up) (van Delden et al., 2010). Indeed, there can be flows of ES in terms of different scales and what happens at one level has an influence or impact on another. Newer concepts of global flows, such as telecoupling (a broadly defined term that refers interactions between different locations, i.e. migration), could include a multiscale approach. In addition, the telecoupling idea can be utilised as a way to capture ecological debts among regions (Lenzen et al., 2012). This is where natural capital accounting and the analysis of international trade is vital (Hein et al., 2015, Moran and Kanemoto, 2017). The EXIOBASE database for input-output analysis (Wood et al., 2014) focuses on the tracking of environmental causes. The database and its broader analytical framework provides a detailed analysis of impacts from production as well as monitoring the effect of consumption patterns (Hubacek et al., 2016). One option to tackle this challenge is the use of Gravity models (Sen and Smith, 2012) as currently undertaken in various social sciences (e.g. in territorial planning) to describe and predict certain behaviours that mimic gravitational interaction. Generally, social science models contain some elements of mass (i.e. Gross Domestic Product, population) and distance (i.e. physical distance, trade barriers, environmental standards, etc.), which is why they lend themselves well to the metaphor of physical gravity (Mojtahed, 2007). For example, the use of gravity models could be applied to determine ecosystem functions, which are important to the public, based upon socio-political relationships.

### 2.3 Integrated modelling of social-ecological systems

The new frontier of modelling the interaction between humanity and the environment is best captured by the integration of flexible, scalable and transparent models, avoiding the “one model fits all paradigm” at different levels (Villa et al., 2014). The strength of fully coupled multidisciplinary models is the ability to capture the feedbacks between bio-physical and socio-economic processes. Agent-based models of social behaviour coupled with bio-physical process-based models are becoming popular (Marohn et al., 2013, Murray-Rust et al., 2014). At coarser scales the same is true for integrated assessment models (Garrett, 2015, Ogutu et al., 2017). There are more than 20 global integrated assessment models currently available in environmental policy (Rosen, 2016), all of them behaving differently when comparing models to the ‘natural’ and socio-economic system (Zaddach, 2016).

However, current global models of nature-society-economy often follow a purely natural science or economic paradigm, which may lead to neglecting decisive processes (Malm and Hornborg, 2014, Barfuss et al., 2016). Most current integrated assessment models also assume that demographic variables are exogenously given (Medvinsky and Rusakov, 2011) and the feedbacks and oscillations effects of socio–cultural systems (Turchin, 2007) on pollution and landscape modification are frequently neglected (Rounsevell et al., 2010a). Additionally, most current models do not examine how technological changes influence the growth of the economy, for example, in energy consumption, (see Ikefuji (2008), Sunstein (2015), Nyborg et al. (2016) and Schlüter et al. (2017)). Many agent-based models have proved able to overcome these limitations, albeit for specific case studies. One popular conceptual agent-based framework is the Land Use Dynamic Simulator that has been successfully applied in Vietnam (Le et al., 2008), Ghana (Schindler, 2009), and Inner Mongolia (Miyasaka et al., 2012). The ability to handle many different types of agents renders the agent-based approach well suited to deal with the diversity inherent in the human environment (Balbi and Giupponi, 2010). According to Filatova et al (2013), key methodological challenges for agent- based models to modelling coupled socio-ecological systems include: 1) design and parameterisation; 2) their validation, verification and sensitivity analysis; 3) the integration of socio-demographic, ecological, and biophysical models, and 4) their spatial representation. Rather than full code integration of different model components into agent-based models, recent developments point towards soft-coupling allowing the flexibility to develop individual model components independently (Marohn et al., 2013, Villa et al., 2017). Notwithstanding the challenge of generalizing agent-based models beyond case studies, there is a vibrant research community that has experimented with model up-scaling or coupling with different modelling paradigms to encompass multi-scale feedbacks among different dynamic systems (Mojtahed et al., 2016, Dobbie et al., 2018). This represents an important step in modelling socio-ecological systems and to adapt developed methods and models to other regions. However, reliable simulation of such systems requires agent-based models based on not only key empirical bio-physical data, but also data that capture the human element (Rounsevell et al., 2012). For example, social networks can provide detailed repositories of micro-level data relating opinions and behaviours of various social subjects (Bodin and Crona, 2009, Rathwell and Peterson, 2012, Bell et al., 2016). The idea of "human functional types" (an equivalent of the "plant functional types" defined in Arneth et al (2014)), indicates a call to incorporate representative social agents within socio-ecological models. The inclusion of institutional agents, in particular, could capture a specific government's alternative structure and different policy feedbacks.

### 2.4 Understanding the value of ecosystem services

ES valuation specifically requires a shift in perspective to broaden and generalise the notion of value, traditionally limited to the accounting of monetary values, towards the incorporation of more general values, which allow the whole spectrum of human opinions to be more respectfully represented (Pascual et al., 2017). Valuation is based upon human preferences and social norms, all of which differ greatly across cultures and societal sectors. Characterising the value domain by including different stakeholder perspectives that reflect different value systems and thresholds has become increasingly paramount.

At the same time, even the classical economic valuation approaches should be complemented with social-ecological system thinking. For example, monetary values should be non-linearly related to resource availability: the scarcer the resource, the more valuable the ES becomes (Farley, 2012). However, in conditions of exceptionally scarce service availability, e.g. *beyond* a certain sustainability threshold, it may not make sense to consider (marginal) economic values, but rather to prioritize ecological restoration. In conditions of scarce resource availability *within* the sustainability threshold, (marginal) economic values can be estimated and used in traditional environmental-economic impact methods such as Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA). In such cases, hyperbolic discounting, one of the cornerstones of behavioural economics, might be applied. In conditions of services abundance, valuation functions can exhibit quadratic/parabolic behaviour; for example, abundance of urban trees which can block the sun or view can reduce the values of a service for neighbouring individuals. The concept of value of a resource directly related to its scarcity, which resembles the concept of distance-to-target used in LCA (Castellani et al., 2016), also raises the question of whether an optimal level of service exists for individuals or for societies, even in the form of a dynamic, and thus moving, target.

Alternatives to traditional monetary approaches are also available to quantify the value of ES. For example, Coscieme et al (2014) proposed an alternative method for combining physics- and monetary- based approaches, using the Emergy values for national economies. Emergy is defined here as the current level of solar energy embedded in the consumed resources of a system. In particular, they considered the energy of renewable input flows, i.e. sun, rain, wind, and tide (for coastal ecosystems), soil fertility; these are the flows contributing to the natural functioning of ecosystems, supporting biogeochemical cycles, and enabling the production of all environmental goods and services, including waste and emission assimilation.

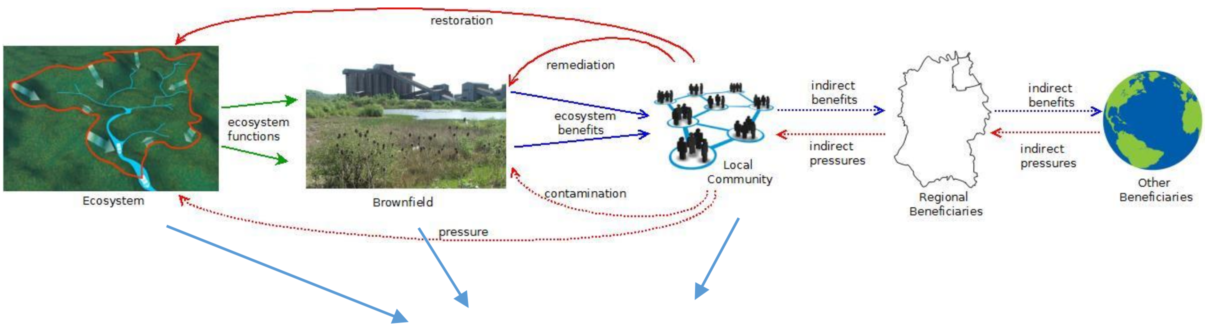
## *3. Brownfield-originated ecosystem services*

The term “Brownfield land”, according to the urban planning community, defines the land utilised for industrial or commercial purposes. Such land may have been contaminated with hazardous waste or pollution. For example, it may feature significant sources of calcium and magnesium rich crushed concrete due to the post-demolition of industrial infrastructure[1]. Brownfield site redevelopment is one of a class of tangible applications that have the potential of contributing to sustainable development (Nijkamp et al., 2002) among other strategies of land use, in that it

[1] Recently, crushed concrete in Brownfield land has been shown to have significant carbon capture potential. Due to the high concentrations of Calcium (Ca) and Magnesium (Mg) silicates that fix the $CO_2$ dissolved in rainwater.

emphasizes broad sustainability goals over the longer term instead of short-term utilisation of resources. According to the U.S. Environmental Protection Agency, Brownfield land is real land and its “development or improvement is impaired by real or perceived contamination” (Solitare and Greenberg, 2002). A more restrictive definition has been proposed by the Small Business and Liability, Relief and Brownfield Revitalization Act (McMorrow, 2003) which defines Brownfields as ‘‘real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant’’. The latter definition highlights how environmental and social concerns (especially in terms of social risk) could strongly affect land-use as well as the utilization of real estate properties. Given the scarcity and the importance of land availability, from both an environmental, economic and social perspective, it is clear that any impediment in land utilization could cause broad impacts on several dimensions. According to the European Environment Agency, in 27 European countries, 1,170,000 potentially contaminated sites were identified, corresponding to 45% of the estimated number of sites that may exist in the EEA-39.

Brownfield land is reported to potentially provide many services which can be harnessed to the benefit of the urban environment and its community (Morel et al., 2015). Rather than simply redeveloping Brownfield land, in their current state Brownfield sites can provide significant benefits. However, because each Brownfield site is unique, a site-specific modelling effort should be proposed in order to assess and grade each site individually. Figure 1 illustrates the dynamics of ES applied to Brownfield land, which easily allows the identification of agents’ classes (i.e. the community, the site and beneficiaries) in a generic agent-based modelling framework. Each site, for example, has a selected number of ecosystem functions, which provide key benefits depending upon location and configuration. In addition, several indirect benefits exist as a by-product of a particular service.



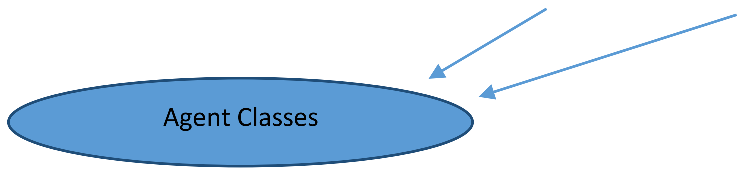



***Figure 1: Dynamics of ecosystem services applied to Brownfield land, illustrating the following steps: (1) ecosystems providing ecological functions to Brownfields; (2) several benefits from this land are delivered to the local community; (3) the community can negatively influence Brownfield land via contamination and can positively influence it via remediation; (4) the community can share benefits with regional beneficiaries (5). Other (global) beneficiaries can be affected by regional beneficiaries via indirect benefits and yet they can also apply pressure so that such benefits are affected.***

The applied scale of measurement, for identifying suitable ES applied to Brownfield land, features a subjective ranking system out of 10 for each relevant ecosystem service. For example, 0-2 indicates very low, 3-4 indicates low, 5-6 is medium, 7-8 is high and 9-10 is ranked as very high and represents the best possible ES potential. These rankings can be used to provide necessary weights for a proposed decision method before stakeholders rank the assumed potential of the ES among the services enumerated in Table 1, climate change regulation (carbon sequestration) and water flows regulation (flood control) score the highest (very high), with the other potential benefits attributed to the decomposing and filtering of wastes. Health, recuperation or enjoyment through active or immersive interactions and historical and cultural significance appear to be also providing promising benefits for Brownfield land.

Carbon emissions can be compensated through artificially engineering soils with selected materials and vegetation so that they have a photosynthesis-driven carbon capture function, for example, through the conversion of atmospheric $CO_2$ to a pedogenic carbonate mineral (calcite, $CaCO_3$). Pedogenic carbonates are formed by plant roots exuding organic acid anions (Renforth et al., 2009, Manning and Renforth, 2012). Non-biological processes of carbonation also occur in alkaline conditions.

In both cases, $CO_2$ partitions into soil porewater as dissolved carbonate, and precipitates by combining with Ca, derived from portlandite ($Ca(OH)_2$), and weathered calcium silicates, originating from materials generated by the demolition process or other natural rock sources. For example, recent research at the former 10 ha site of the Newcastle Brewery (Newcastle Upon Tyne, UK) indicated a sequestration of up to 85 t $CO_2$ $ha^{-1}$ annually (Washbourne et al., 2015b). Naturally, this process will depend upon the type of soil and material that constituted the original building as well as the surrounding area. This rate of absorption is also encouraging due to the lack of biological or organic processes, therefore Brownfield sites that are bare and are stripped of vegetation can still take advantage of the mineral carbonation process, possibly even thriving in this state.

Table 1 lists biotic services which possess significant potential to be realized on Brownfield land.

| **Ecosystem group** | **Ecosystem services** | **Service description (CICES V5.1 Code)[2]** | **Perceived relevance to Brownfield land based on literature** |
|---|---|---|---|
| **Provisioning services** | *Biomass for food production* | Using the land to produce food by growing plants or rearing animals (1.1.1.1, 1.1.3.1, 1.1.5.1). | Low, due to possible contamination and lack of soil organic biomass (Jennings et al., 2002) |
| | *Biomass for direct use or processing* | Using the land to produce fibres and other materials by growing plants or rearing animals (1.1.1.2, 1.1.3.2, 1.1.5.2). | Medium. More work needs to be studied on the effects of plants in highly mineralised urban soils (Jorat et al., 2015a). |
| | *Biomass for energy production* | Using the land to produce biomass for energy production by growing plants (1.1.1.3, 1.1.5.3). | Medium. Same as above |
| **Regulating and maintenance services** | *Regulating conditions of fresh water* | The ability of the land to regulate quality of fresh water (2.2.5.1). | Low, due to possible soil contamination (Jennings et al., 2002). |
| | *Regulating the flows of water* | The capability to store water and reduce impact of flooding by slowing down runoff (2.2.1.3). | Very High potential for superior water management (Apostolidis and Hutton, 2006) |
| | *Decomposing and filtering wastes* | The ability to control the dissolution of contaminants in the soil and groundwater (2.1.1.1, 2.1.1.2) | High. Preventative measures may be put in place in order to reduce chemical runoff (Conesa et al., 2012) |
| | *Regulating air quality and global climate* | The capacity to regulate air quality, atmospheric processes and microclimate. For example, geoengineering (2.2.6.2). | High. Urban soils possess high potential to sequester $CO_2$ which on a large scale possess the capability to affect global climate change (Washbourne et al., 2015a) . |
| | *Biodiversity lifecycle and diversity maintenance* | The ability to provide habitat for a diversity of animal and plant species including genepool protection (2.2.2.3). | Low to medium. Due to the large variance in Brownfield sites, biodiversity will be affected significantly (Pascual et al., 2015) |
| | *Regulating pests and invasive species* | Controlling foreign species whose introduction causes or is likely to cause harm (2.2.3.1). | Medium. Brownfields have potential to carry a wider diversity of species (Harrison and Davies, 2002) |
| | *Atmospheric carbon capture* | The ability of the soil to absorb $CO_2$ through biomass and/or mineral carbonation via the soil substrate (2.2.6.1). | Very High, Urban soils possess high potential to sequester $CO_2$ due to the presence of calcium and magnesium (Washbourne et al., 2015a) |
| | *Soil formation, maintenance and soil retention* | Developing soil by fixing and maintaining organic matter and preventing soil loss (2.2.4.1, 2.2.4.2, 2.2.1.1) | Medium. Although there is variability in the configuration of Brownfield land, engineered soil could be used to ensure organic matter is retained (Sparke et al., 2011) |
| | *Noise and smell control* | The ability to reduce noise and smell within the area (2.1.2.1, 2.1.2.2) | Low. Due to the former industrial use of most Brownfield sites, the production of odour and noise tends to originate from these areas, particularly where incinerators are being used (Casado et al., 2017) |

[2] https://cices.eu/

| | | | |
|---|---|---|---|
| **Cultural services** | *Health, recuperation or enjoyment through active or immersive interactions* | Attracting and retaining visitors wishing to relax, explore and stay fit (3.1.1.1). | High. There is potential to place Brownfield land as a public space to relax and also providing pathways and cycle routes (Martinát et al., 2014) |
| | *Historical and cultural significance* | Using the land to determine the history and cultural heritage of the area and its relevance (e.g. old factory chimneys in traditionally industrial cities) (3.1.2.3). | High. Brownfields within city centres may contain culturally valuable buildings which can attract tourists and the local public (Alker and Stone, 2005) |
| | *Aesthetic experience* | Providing environmental spaces where people interact with each other and can admire the beauty of the nature (3.1.2.4). | Medium. Carbon capture gardens can offer places of beauty through the placement of selective vegetation and engineered soil for $CO_2$ sequestration (Renforth et al., 2011) |
| | *Scientific studies and education* | Researching, studying and learning about the nature (3.1.2.1, 3.1.2.2). | Medium to High. As above, carbon capture gardens could attract visitors who wish to learn interactions between plants and soils (Renforth et al., 2011) |

***Table 1: Potential ecosystem services for Brownfield land***

As the frequency and size of flooding events increase, affected by climate change, greening Brownfield land (green spacing) within the town or city could be used to reduce velocity of local rainwater runoff and can act as buffer zones (controlled flooding which avoids introduction of water runoff in residential areas). The risk of flooding and the necessary management procedures that mitigate it contribute to an essential ES for urban areas, where climate scenarios suggest increased rainfall variability and natural hazard probability (Xiao et al., 1998, Moffat and Hutchings, 2007, Gans and Weisz, 2004). In particular, the emphasis is on plots of land close to areas such as highways, rail networks or other residential areas where flooding is a major concern, provided that there are no extensive paved areas at the Brownfield site. The introduction of various types of vegetation may also be able to enhance the public perception of Brownfields. However, based on EU legislation this will depend on the amount and type of pollutants that are present at the Brownfield site, if not yet remediated.

# *4. A workflow for ecosystem-based Brownfield assessment*

## 4.1 Brownfield redevelopment

Brownfield redevelopment (BR) initiatives are relevant not only for restoration of certain areas and the reuse of previously abandoned spaces, but also for their deep interconnection with community social-economic regeneration, job creation, and health and safety preservation. BR can happen through steady improvements over time by means of minor changes, allowing the creation of additional value through restoration and reuse, and increased synergies between sustainability and preservation perspectives. This is not limited to including the development of alternatives for the development of Greenfield sites (Dorsey, 2003). Although the majority of the early literature discusses the conversion of Brownfield sites to Greenfields or “Greenbacks”, recent literature has focused on assessing the potential benefits of Brownfield's in their current state and condition. Such services may include carbon capture — a by-product of the demolition processes with resultant minerals within crushed concrete — that lie in urban soils (Jorat et al., 2015b). Actually, policies geared toward Brownfield reuse effectively reduce barriers to infill development on existing urban lands, thereby relieving development pressure — as well as enhancing a lighter carbon footprint — from Greenfield exurban sites. An ecosystem-based decision support workflow should build on integrated ES models, as per Section 2, extrapolating static indicators from dynamic simulations according to assessment needs. We refer here to a complexity-embracing approach, radically different from mainstream ES practice. Simpler indicator-based frameworks can then be used to elucidate the ecosystem-driven priorities in terms of redeveloping or altering a Brownfield site based upon the configuration of the plot of land and the public perceptions towards it.

Any complexity-embracing process will imply valuation that mediates different values or preferences. This can be addressed through a methodology that can handle conflict (we further expand on this in section 4.2.4). Our suggested approach is to combine Dempster-Shafer theory (DST) for capturing uncertainty with multi-criteria decision making, allowing for individual stakeholder weightings of any particular ecosystem or site (Tayyebi et al., 2010, Kolosz et al., 2013). Preferences can then be generated within the public sustainability perspective, based on realistic ES assessments and illuminating the costs and benefits of redevelopment. The integrated modelling of ES leads to a contextual case study where goal definition and scoping is formed and an inventory and boundary analysis of the land is conducted. An impact assessment on the previous land use through Territorial LCA is performed which leads to the identification of a bundle of key ES. Socio-ecological data is handled through public ranking in order to provide weights to the ES. Measured ES with appropriate targets and thresholds are interpreted from environmental, social and economic perspectives. It is at this point that other beneficiaries (see Fig.1) can be taken into account. ES are prioritised after data fusion with the probabilistic method DST, then a CBA analysis provides overall economic conclusions. Finally a redevelopment and optimisation index provides an overall performance result for the land providing recommendations and approval to the BR strategy. Figure 2 describes the breakdown of tasks necessary to proceed through the workflow. This includes:

1) Goal definition and scoping
2) Inventory analysis for LCA and ES data sources
3) Territorial LCA of Brownfield
4) Identification and estimation of ES performance
5) Optimisation and redevelopment strategy.

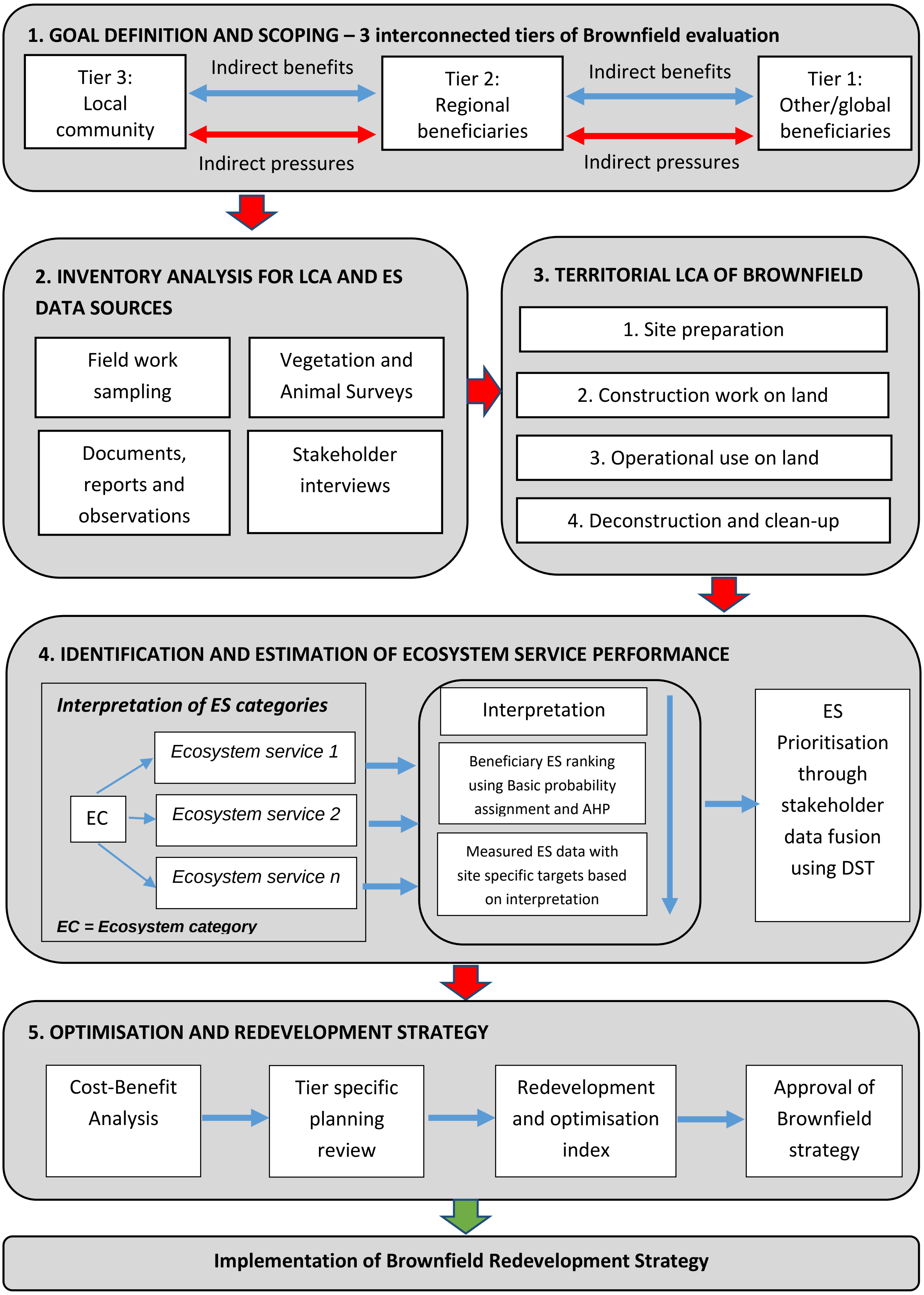



**Figure 2: Integrated ecosystem services redevelopment workflow for Brownfield land**

## 4.2 Workflow stages

### *4.2.1 Goal definition and scoping*

In the first stage of the workflow, the goal and scope is defined and categorised into three distinct redevelopment tiers linking local, regional and other beneficiaries (see Figure 1). Tier 1 aims to consider redevelopment strategies representing global beneficiaries. At this scale, indirect beneficiaries are key due to the broad impacts of the redevelopment workflow and the broad diversity of each site. For example, Brownfields that possess a significant carbon capture function would improve climate regulation for the wider general public, beyond the surrounding area. Local beneficiaries would additionally enjoy ancillary benefits deriving from ES that have improved despite not being a priority, e.g. local air quality etc. Tier 2 focuses on redevelopment strategies for a single region, while Tier 3 focuses on an individual site on behalf of the local community. As the workflow provides a continuous gradient in terms of implications at different scales, the 3rd tier would be applied first to deal with the reassessment of varying types of Brownfield land. Such reassessment would eventually bear implications at wider scales involving other beneficiaries as redevelopment protocols become standardised.

### *4.2.2 Inventory analysis for LCA and ES data sources*

In the second stage of the workflow, it is important to determine what the site was originally used for, through inventory analysis, as it may contain a number of contaminants and embedded emissions. For example, Brownfield sites which formerly hosted (now demolished) buildings will contain a significant amount of embedded emissions due to construction, usage, and eventual demolition. Current ES performance can then be estimated which provides input to the Territorial LCA (step 3) as well as assisting in the identification and estimation of ES performance.

Field sampling is carried out to determine factors such as soil composition and chemical makeup, as well as to determine the presence of contaminants. Samples are collected to decide which ecosystem indicators can appropriately describe the area that has been selected. Vegetation and ecological surveys are also carried out. Based on EU legislation (Brookes, 1995), it is necessary to perform systematic soil sampling in order to check for pollutants (not just historical data), which define appropriate soil remediation methods and the decontamination targets to be reached, depending on new functionality. Historical documents and reports can provide detailed background knowledge of what the site was previously used for, as well as direct observation and further collection of field data. Stakeholder interviews may also serve this purpose, particularly companies that previously used the site. Direct observations relate to physical inspection and stakeholder interviews consist of communication with the public, land owners and project managers that have a vested interest in BR.

### *4.2.3 Territorial LCA of Brownfield*

Territorial LCA (Loiseau et al., 2018) focuses on the assessment of a specific activity taking place in a given territory, and can assess all the processes located in that territory or even attempt to include all environmental pressures embodied in trade flows with other territories as a result of the studied activity (such as a BR plan). The four key LCA stages (cradle-to-grave) are:

1. Site preparation
2. Construction work on land
3. Operational use on land
4. Deconstruction and clean-up

Site preparation (1) consists of the remodelling of the Brownfield land and precedes construction. During this phase, land may be flattened, reshaped and the possible relocation of wildlife is carried out. In addition, this step also takes into account emissions resulting from any machines or equipment that are used in this process. Construction work on land (2) consists of the emissions generated from the assembly of buildings and machines necessary for the lands primary function. The operational use on land (3) is carried out for the entire duration of use until it is no longer of use. Any buildings or installations that generate emissions and contaminants as well as use electricity will be included in this step. The final step – deconstruction and clean-up (4) - consists of the removal and restoration of the land to its previous state.

### *4.2.4 Identification and estimation of ES performance*

At this stage, ES are selected and grouped into categories based upon the findings of the inventory analysis in step 2. The ES are then interpreted contextually. In order to prioritise actions and determine the benefits of BR in achieving goals at different scales, it is fundamental to include the perspectives of multiple stakeholders by means of a multi-criteria decision approach. In this context, we suggest an approach similar to the one carried out by Wedding and Crawford-Brown (2007) who applied an Analytic Hierarchy Process (AHP), a method for multi-criteria analysis of complex problems applied in group decision making (Saaty, 1980). The choice of indicators for this analysis is fundamental and results are likely to be sensitive to their selection. To cover all the dimensions of sustainability, indicators were chosen to fit four primary categories: environment-health, finance, liveability, and socioeconomic performance. Based on an expert survey, a weight was given to each specific indicator. Both indicators and weights are chosen by selected experts, so it is important to acknowledge the subjectivity of this exercise. Values are then assigned by the AHP algorithm to each ES and can be used to determine relative priorities.

Methods aimed at decision makers are often requested to produce overall indicators that summarize performance, fitness or status in one easily understandable number. This practice averages the entire complexity of a case study, with the potential of trivializing the internal structure of a complex situation, and must therefore be undertaken with great care. We find it productive to present results in a way that respects the underlying complexity, such as in the case of AHP, which clearly tracks priorities between criteria. By converse, DST is a useful way to combine multiple socio-environmental variables into a single measure of performance, as long as this is presented in a way that emphasizes the risk of using any aggregated indicator as the sole criterion for decision. DST and AHP essentially operate together as two independent but synergic steps. The key characteristic of DST includes the ability to handle uncertainty, such as missing or incomplete data, as well as the ability to combine different data types (Awasthi and Chauhan, 2011, Dempster, 2008, Shafer, 1976, Yao et al., 2012, Kolosz et al., 2013). These methods possess well-known limitiations. For AHP, there may be a great deal of pairwise comparisons required, which in turn depend on the data supplied. One possible solution is to reduce the number of hierarchies and incorporate the comparisons into specific groups. For DST, results may sometimes be tautological in the sense that they simply prove if a certain body of evidence is accurate or not.

The next step of the workflow consists of providing measured ES data with targets. Scales of measurement have an impact on total ES value (Konarska et al., 2002, Feld et al., 2009, Robertson, 2012). The scale of measurement is decided based upon the focal tier in the first step of the workflow. Standardised spatial scales of measurement must be agreed upon and used. As the analysis moves between different tiers, increased scales of measurement are carried out. Target setting is dependent on ES prioritisation and is decided by multiple stakeholders and evidence from the Brownfield inventory analysis (step 2). The target method used is an enhanced version of the distance-to-target method (Castellani et al., 2016). It allows targets for each ES to be adjusted based on the distance and year that this target aims to be reached. The sources for ES data are derived from the inventory analysis and are context specific, depending on the focal tier that is currently in focus.

The final step involves reducing uncertainty related to ES modelling through integrating the subjective opinions of different stakeholders using DST. The performance beliefs of each stakeholder can be separated into individual sources from which probabilities are inferred. Eventually, these probabilities can be combined with various fusion operators to model semi-quantitative ES performance, e.g. very low to very high. This approach is carried out using the methodology proposed by Kolosz et al (2013). The final outcome of this phase feeds into the cost benefit analysis of step 5, i.e. the optimisation and redevelopment strategy.

#### *4.2.5 Optimisation and redevelopment strategy*

At this stage a redevelopment project is drawn. The economic approach for evaluating projects is commonly based on CBA, which in this case, would focus on the comparison of all gains (benefits) and losses (costs) related to Brownfield remediation and reuse (Alberini et al., 2005). Turvani and Tonin (2008) have demonstrated how CBA of BR can be inspired by the sustainable development perspective. The authors divided the costs into two groups: direct costs, and indirect costs, linked to the opportunity costs and to the effectiveness of BR. Benefits have been classified by the investigators into the three pillars of sustainability. Environmental benefits include the reduction of pressure on developed Greenfield, protection of human health, water resources, and soil preservation, i.e. recycling, restoration of former landscapes and the institution of new ecological valuable areas. The social benefits incorporate the renewal of urban areas, the improvement in the quality of life, the reduction of negative social stigma associated to the affected community, the reduction of risk and fear perception in the community, reduction of risk of death or illness. Economic benefits could derive from the attraction of investment (both domestic and foreign), the restoration of local tax base, the increase in employment opportunities, the enhancement of local economy, the improvement of infrastructures and municipal services, and the incentives to remediation technology investments. Indeed, the quality of the outcome of a CBA is dependent on how accurately costs and benefits have been estimated, and the estimation of costs and benefits through stated preferences can also be affected by bias due to the responders. In addition, the discount rate used for present-value calculations is an arbitrary choice of the researcher, but can be very controversial and can affect significantly the evaluation of a project.

After the CBA has been completed, the monetary results are fed into the tier specific planning review. This planning review depends upon the context of the analysis and tier of focus that the workflow represents. In the case of Brownfields, the planning review would guide the redevelopment process within the context of the local area under investigation. For example, tier 3 would relate to a city based level of impact while tier 1 would focus on a global scale, exploring the impact of a certain type of Brownfield land. The redevelopment and optimisation index constitutes the final quantitative results of the workflow providing current and potential performance rankings of all of the ES expressed in a CBA compatible fashion.

### 4.3 Application of workflow example: Carbon capture gardens

As part of a global initiative on Greenhouse Gas reduction (GGR) one relevant example application for the workflow, could apply to the assessment of potential redevelopment of existing Brownfield land into carbon capture gardens at multiple scales. According to Renforth et al (2011), the soil carbon capture function is highly applicable to the constructed environment in urban areas and should be considered when planning for existing or new developments. For example, the total carbon capture potential of soils in cities may be as high as 7 Mt $y^{-1}$ if using accumulated carbon materials. In step 1 (goal definition and scoping), the appropriate tier is selected to determine the level of focus. In tier 3, the focus is on the impact the carbon capture garden would have within a single cityscape. On a more regional basis, tier 2, the impact of multiple Brownfield sites being transformed into carbon capture gardens is explored across areas with different configurations, including highway land and airports for example (Jorat et al., 2017) and finally, tier 1 would aim to quantify the impact of the revised Brownfield configuration on the global carbon cycle, showing direct and indirect impacts of GGR through mineral carbonation. Indirect benefits of implementing carbon capture gardens may include improved air quality and social wellbeing due to the growing of plants that can act to pump $CO_2$ into the soil where carbonates can form. Indirect pressures may consist of potential incompatibility of the selected urban soil material impacting local wildlife and vegetation, causing potential crop failures.

In step 2, for the inventory analysis, different calcium rich substrates and vegetation are selected depending on their availability. These substrates all possess different quantities of minerals which can affect the performance of the carbon capture function. For example, cement kiln dust and steel making slag possess average CaO (calcium oxide) percentages of 60-65% and 45% respectively. It is also important at this stage to determine how urban soils would interact with the land, for example, how plants grow in such substrates is of particular importance (Jorat et al., 2015a, Renforth et al., 2011). As plants act as a $CO_2$ pump, suitable vegetation such as green compost must be selected to maximise the mineral carbonation process, in addition to cosmetic appearance. In step 3, the territorial LCA of the site is performed to determine the potential savings of $CO_2$ as well as to determine the potential for a carbon sink. In step 4, ES that are estimated to be available are selected and categorised based upon the prioritisation of the carbon capture function. Finally, in step 5, a CBA is performed, potentially including savings in the form of $CO_2$ offsetting. The tier specific planning review includes all of the necessary details to promote and deliver the carbon capture function within the city and the local region as well as its strategic key placements.

## 5. Conclusion

The original foundation of ES research has been the categorization of nature into separated ecological functions providing certain benefits to human societies. However, at this point in time, the concept of ES is better interpreted as a means to connect ecosystems to human beneficiaries (and vice versa) in a systemic way, rather than a simplistic take on the quantification of ecological processes and functions of natural resources, from an anthropocentric perspective. Recognizing the need for a complexity-oriented approach, modern ES modelling techniques are improving the accounting of non-monetary nature-based flows to society by addressing the problem in an interdisciplinary fashion. Ecosystems are thus studied considering both ecological and socio-economic dynamics and interactions that, in turn, exert pressures on them.

We maintain that ES modelling should operate under a new interdisciplinary modality, best approximated via integrated models, which are able to represent the wide variety of dynamics and interactions that happen within social-ecological systems at multiple spatial and temporal scales — including irrational human behaviour, market prices volatility, local versus global economy, global environmental change — without the limitations imposed by a single modelling paradigm (e.g. system dynamics vs. agent-based modelling).

Significant challenges are posed by cutting-edge modelling requirements like (a) the continuous integration of individual elements constituting the system components (i.e. agents and their attributes, processes and events, relationships, etc.) (Villa et al., 2017); (b) the ability to understand and represent indirect and nonlinear structural and functional connections; (c) the ability to investigate possible futures and alternative scenarios (e.g. policy testing), while capturing the associated uncertainties, and to explore their consequences using models as virtual laboratories (Kwakkel and Pruyt, 2013).

At the same time, models are man-made constructs that incarnate subjective ways of deciphering reality from a certain viewpoint and need to be contextualized within the scope for which they were developed. Arbitrary model use may inform decision makers with wrong conclusions, if only model outputs are taken into account, more so if there is a lack of understanding of model performance or, models do not match the spatial-temporal scale(s) of the problem(s) at stake.In this article, we have taken a broad view of the current state of the art in integrated social-ecological modelling, with a focus on Brownfield originated ES. Via the example of BR, the paper proposes a sustainability-oriented modelling workflow that weaves together different sub-models to build a comprehensive simulation design where natural, social and economic agents (e.g. community, site and beneficiaries) can interact.

Addressing the contribution of Brownfield land to people is a vital piece in a set of urban planning strategies that connect local actions to global change phenomena and vice versa. Social and individual behavioural traits greatly influence the ways ES, as any other asset related to human life, are perceived and valued. Thus, the proposed workflow is also respectful of the perceived benefits, constantly in flux with the needs of local socio-ecosystems (i.e. humans, animals and vegetation).

Apart from its impact on ES, a BR plan may have additional impact on socio-economic parameters. For example, we can imagine that once the redevelopment plan is implemented, it may influence the tax base of the jobs created. Additional research, not covered in our workflow, could investigate these further stages using agent-based simulation whereby individual Brownfield sites are tracked through the redevelopment process. Studying the spatial distribution and effects of Brownfields and redevelopment activities along with the interaction of Brownfields (seen as agents) within the larger urban system, can elicit additional emerging features to inform the policy debate. One example is the formation of a municipally controlled land bank which undertakes the redevelopment of Brownfield land soon after a property is foreclosed through tax (BenDor et al., 2011).

This article represents an initial step towards a more compelling and fruitful integration of ES models into BR evaluation.

## Author acknowledgements

Most of the ideas presented in this article emerged during the A2 workshop, titled "Integrated Socio-Ecological Modelling for Ecosystem Services and Beyond", at the 8th congress of the International Environmental Modelling and Software Society

(iEMSs 2016, Toulouse, 12th of July). All authors apart from Ben Kolosz and Stefano Balbi are listed in alphabetical order.

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