SPECIAL FEATURE: ORIGINAL ARTICLE

Exploring Interactions among the Sustainable Development Goals: Case Studies from Three Continents

Analysing trade-offs and synergies between SDGs for urban development, food security and poverty alleviation in rapidly changing peri-urban areas: a tool to support inclusive urban planning

Jonathan Dolley[1] · Fiona Marshall[1] · Bradley Butcher[2] · Jeremy Reffin[2] · James Alexander Robinson[2] · Baris Eray[2] · Novi Quadrianto[2]

Abstract

Transitional peri-urban contexts are frontiers for sustainable development where land-use change involves negotiation and contestation between diverse interest groups. Multiple, complex trade-offs between outcomes emerge which have both negative and positive impacts on progress towards achieving Sustainable Development Goals (SDGs). These trade-offs are often overlooked in policy and planning processes which depend on top-down expert perspectives and rely on course grain aggregate data which does not reflect complex peri-urban dynamics or the rapid pace of change. Tools are required to address this gap, integrate data from diverse perspectives and inform more inclusive planning processes. In this paper, we draw on a reinterpretation of empirical data concerned with land-use change and multiple dimensions of food security from the city of Wuhan in China to illustrate some of the complex trade-offs between SDG goals that tend to be overlooked with current planning approaches. We then describe the development of an interactive web-based tool that implements deep learning methods for fine-grained land-use classification of high-resolution remote sensing imagery and integrates this with a flexible method for rapid trade-off analysis of land-use change scenarios. The development and potential use of the tool are illustrated using data from the Wuhan case study example. This tool has the potential to support participatory planning processes by providing a platform for multiple stakeholders to explore the implications of planning decisions and land-use policies. Used alongside other planning, engagement and ecosystem service mapping tools it can help to reveal invisible trade-offs and foreground the perspectives of diverse stakeholders. This is vital for building approaches which recognise how trade-offs between the achievement of SDGs can be influenced by development interventions.

Keywords SDG trade-offs · Food security · Peri-urban · Inclusive urban planning

✉ Jonathan Dolley
  J.Dolley@sussex.ac.uk

1 SPRU - Science Policy Research Unit, University of Sussex Business School, University of Sussex, Falmer, Brighton, UK

2 Informatics, School of Engineering and Informatics, University of Sussex, Falmer, Brighton, UK

Introduction

In the course of implementing strategies to achieve the United Nations' SDGs, it will become increasingly important to find ways to maximise the synergies and negotiate difficult trade-offs between various goals in different contexts (Bowen et al. 2017). One of the most significant contexts of such synergies and trade-offs is rapid urbanisation. Trade-offs between urban development, poverty alleviation and preserving ecosystem are especially acute at the peri-urban interface in rapidly urbanising contexts (Marshall et al. 2018). Urban expansion places increasing pressures on near and distant natural resources and progressive replacement

of agricultural land and degradation of ecosystem services[1] as cities expand (Parnell 2016; Seto et al. 2017). Peri-urban transition zones are key 'frontiers of sustainability' (Marshall 2016) with contestation and negotiation concerning land-use change, and service provision and associated governance arrangements, which will have major and long-term implications for environmental integrity and the health and livelihoods of residents across the rural–urban continuum (Marshall et al. 2016). The impact of peri-urban land-use change on agricultural production is an obvious example in which a direct trade-off exists between maintaining the supply of locally produced food and the economic and social benefits of urbanisation. This trade-off is particularly important in contexts where a large proportion of fresh produce for urban markets is grown in peri-urban areas, such as is the case in many Indian (Marshall and Randhawa 2017) and Chinese (Gu 2009; Simon 2008; Wu et al. 2014) cities.

However, the trade-offs involved are more complex than simply between economic growth and aggregate food supplies (which could be argued are replaceable through imports). A food system perspective on food security (Ericksen 2008a, b; Misselhorn et al. 2012) reveals the importance not only of the quantity of food produced but also of its distribution, accessibility, quality and safety, all factors that are influenced by land-use planning decisions, and the proximity of agricultural land to other land uses. A broader perspective on food security also encompasses attention to the livelihoods of people dependent on the production and marketing of food, in addition to consideration of the ecological impacts and benefits of food production and processing practices, and to the potential for more sustainable use of natural resources (for example, recycling of water, enhancing soil fertility without external inputs). This demonstrates important interactions between multiple SDGs including food supply and safety for different groups (SDG 2—Zero hunger), livelihoods of different groups of farmers (SDG 8—Decent work and economic growth), environmental health (SDG 3—Good health and well-being) and ecological integrity (SDG 15—Life on land).

The complex dynamics of the peri-urban context present additional challenges to understanding and governing trade-offs. The peri-urban interface is often characterised by: rapid land-use change across a highly heterogeneous landscape shaped by diverse interests and flows of people and resources; the juxtaposition of rural and urban land-uses; a high degree of informality and overlapping and ambiguous institutional arrangements (Marshall et al. 2009). These are contexts of previously unchartered development trajectories,

full of uncertainty and surprise as new, unexpected or poorly recognised interactions across socio-technical ecological systems arise, resulting in not only new trade-offs, but also opportunities for synergy building (Marshall and Dolley 2019). Thus, established models of expected SDG interactions may not apply. However, current formal decision-making is often not informed by understanding of current actual peri-urban land-use practices, or information on the trade-offs and synergies that evolve as one land use practice is juxtaposed with another in fragmented peri-urban spaces.

This raises the question of how urban land-use planning decisions can be better informed to reduce trade-offs and build synergies between SDGs. How can urban planning decisions be supported to take account of the environmental, poverty and food security implications (including livelihoods, food safety, etc.) of peri-urban planning decisions alongside goals of GDP growth, infrastructure improvement and employment generation? What sort of mapping tools and data would be required to support a broader and more joined-up approach to city-region ecosystem-based planning?

In this paper, we draw on a case study of peri-urban development in Wuhan to explore the complex SDG trade-offs involved in land-use planning in peri-urban China. We then describe the development of a web-application to provide a novel user-friendly method for mapping land-use change in peri-urban contexts, analysing SDG trade-offs associated with different scenarios of land-use change and supporting participatory processes for further analysis of possibilities to build synergies across efforts to achieve SDGs in land-use strategies, and in support of urban planning. Finally, we discuss the ways in which this method can help to make these trade-offs more visible in the planning process.

Case study description

Wuhan, situated on the Yangtze river, is the capital of Hubei province and the largest megacity in central China. It had a population of 10.7 million by 2016 and covers an area of 8569 sq. km (WH 2017). It has 13 districts including six densely urbanised central districts, one largely urbanised district and six outer districts containing smaller urban centres and large areas of agricultural lands, villages, state farms, forested areas and lakes.

Despite rapid and large scale urbanisation over the past decades, the municipality of Wuhan has retained a substantial proportion of cultivated areas (WH 2017). While grain production in Wuhan has declined over the past decade, vegetable production has rapidly increased even as the total area of cultivated land has steadily declined (WH 2017; 2010). This indicates ongoing intense competition for land-use in Wuhan's peri-urban areas and increasing intensification of

---

[1] We adopt a broad definition of ecosystem services as nature's contributions to people (see Díaz et al. 2015; MEA 2005; Pascual and Howe 2018).

remaining agricultural production. It is in this context that the impact of peri-urban land-use planning decisions on trade-offs between SDGs need to be understood.

For this case study, we have reinterpreted data from ESRC-funded PhD fieldwork concerning peri-urban food systems in Wuhan which was conducted between 2011 and 2012 (Dolley 2017). These data have been added to and analysed to explore methods for understanding trade-offs between SDGs in urbanising contexts.[2] "Box 1: Fieldwork data", summarises the original findings that are relevant to the present discussion and the following sections describe the different perspectives on SDG trade-offs revealed by the re-analysis.

Box 1: Fieldwork data

One of the aims of the original PhD research (Dolley 2017) was to understand the significance of peri-urban vegetable production for Wuhan's urban food security and analyse the impacts of urbanisation on the changing peri-urban food system. The research was designed to explore the outcomes of the peri-urban food system for food security (including affordability of vegetables and issues of food safety), the livelihoods of different groups and elements of environmental integrity.

Methods

Semi-structured interviews were conducted with 60 peri-urban farmers in 20 locations around the city and with 11 business people engaged in farming and vegetable distribution, several government officials and academics. As data on the spatial distribution of different types of agriculture was unavailable from formal sources, visual analysis of high-resolution Google Earth aerial imagery from multiple points in time between 1999 and 2013 was conducted to map the changing distribution of different types of agriculture and the process of urban development in Dongxihu district, one of Wuhan's outer districts.

Summary of findings

It was found that intensive cultivation of leafy greens and fruiting vegetables in peri-urban areas was critical to ensuring the supply of affordable vegetables through urban markets while also providing livelihoods for marginalised farming households who had migrated (usually as a household unit—parents with children and

---

sometimes grandparents together) from poor rural areas to escape poverty. On the other hand, root vegetables and grains were sold mainly through provincial or national markets and were less critical to local food security.

Visual analysis of high-resolution aerial imagery of Wuhan's peri-urban vegetable production areas suggested that a large proportion of intensive vegetable farmers were migrant households. This observation was made based on the presence of small houses on the corners of cultivated fields which are absent from vegetable fields cultivated by local farmers who live in formal housing in villages. Interview data showed that these migrants informally rented lands from local farmers or state farms close to urban areas; they typically supplied perishable vegetables through local wholesale markets (for sale to Wuhan's urban population); and vegetable farming was usually their sole livelihood.

These intensive vegetable farming areas tended to be located as near as possible to urban areas for two main reasons. First, to reduce transportation costs for farmers taking produce to local wholesale markets. Second, when local farmers become more involved in urban employment and when rural lands are designated for future redevelopment in master plans, local famers lose any incentive to continue cultivating their land while they anticipate a compensation payoff in the near future. Instead, it becomes more convenient to rent lands to migrant farmers.

One of the implications of this is that intensive vegetable cultivation is often located near to industrial areas on the periphery of the city (such as the Qingshan site in Wuhan where intensive vegetable production is surrounded by steel and oil industries, factories and a power station) which present potential contamination risks to food production (Agrawal et al. 2003; Hu et al. 2014; Si and Scott 2016; Singh et al. 2010; Zhang et al. 2015).

Further, the relatively short time-scale available for cultivation and the anticipation of the imminent redevelopment of agricultural lands means that vegetable farmers lack any incentive to adopt farming practices with low environmental impact. On the contrary, it is in farmers' interests to apply as much chemical fertilizer and pesticides as they can afford to boost yields and increase incomes in the short term.

For migrant farmers, due to their informal status (holding non-local rural hukous[3]), when the land they cultivate

---

[2] Funded by the Sussex Sustainability Research Programme (URL: https://www.sussex.ac.uk/ssrp/).

[3] China's system of household registration (the hukou) divides the population into rural and urban classes and ties access to public services and employment rights to a persons' location of residence (Young 2013). Relocating from a rural village to the outskirts of a megacity involves becoming an informal migrant without formal rights to residence or urban services.

is finally occupied for urban development, they lose their fields, livelihoods and homes and rarely receive compensation. Their only option at this point is to find alternative locations further from the city to begin vegetable farming over again. Many of the farmers interviewed had already been displaced one or more times from locations nearer to the city centre and expected to be moved on again within 2 or 3 years. Analysis of historical google earth imagery confirmed that this process of displacement had indeed occurred several times and in multiple locations across Wuhan.

Local households, on the other hand, can expect to receive financial compensation for the loss of land and compensation for lost houses in the form of replacement urban housing proportionate to the area they had lost. Of course, these compensation arrangements may be perceived to be unsatisfactory to some but to many the loss of lands and homes to urban development represents an opportunity for a better life, gaining a stake in the rising urban housing market and enjoying access to urban public services previously unavailable until their hukou was changed from rural to urban.

SDG trade-offs from a planning perspective

Recognising the most obvious trade-offs, a land-use planning decision on urban expansion may consider the need for more housing (SDG 11.1) alongside the economic and employment benefits of new industrial zones (SDG 8) and the environmental health benefits for urban citizens of relocating polluting industries (SDG 3) against the need to preserve agricultural land for the sake of food security (SDG 2).

If planners only consider the productive potential of agricultural land and the aggregate economic benefits of redevelopment (without reference to spatial or social distribution) then it is easy to conclude that any loss can be compensated by either the intensification of remaining agriculture, converting suitable uncultivated land further from urban areas to agriculture or simply increasing dependence on distant agricultural production facilitated through national or global markets. The main obvious trade-offs from this perspective are between the aggregate economic benefits of urban development and the potential economic and environmental costs of making up for the loss of productive agricultural land. From the perspective of the core interests of many of the urban population, it might appear that mitigating this trade-off will only require action to ensure reliable food supplies to the city and policies to prevent the loss of the most valuable natural habitats.

The mix of policies in Wuhan (and indeed across China) reflects these trade-offs. Wuhan's vegetable industry

development policy has long been designed to support the scaling up and intensification of production of plastic greenhouse vegetable production to maintain urban vegetable supplies despite progressive loss of agricultural land (WAB 2012; WAB Director 2012). At the same time, Wuhan also began implementing China's 'Ecological Control Line' (ECL) policy in 2009 by, among other things, designating conservation areas and basic cropland to be protected from redevelopment in the 2010–2020 Masterplan (Luo et al. 2018). Additional supporting policies were introduced in 2012 to better regulate urban sprawl and protect ecological resources in support of urban and peri-urban ecosystem services (Luo et al. 2018). On the other hand, China's strict Cropland Balance Policy requires the municipal government to compensate for the unavoidable loss of cropland to non-agricultural construction through cropland reclamation, usually from natural or semi-natural land (Zheng et al. 2018).

Addressing these trade-offs, however, is not as simple as these policies imply. Zheng et al. (2018) predict that in Wuhan and other rapidly urbanising cities, the greater the area of compensated cropland the worse the trade-off between compensated cropland quality (i.e. potential agricultural productivity) and the incurred cost in terms of loss of ecosystem services. This implies that even if cropland lost to urbanisation is replaced elsewhere the net impact on food supply and ecosystem degradation is most likely to be negative.

Further, a range of other hidden trade-offs is revealed by a more grounded perspective that disaggregates the diverse interests of different stakeholders and recognises the processes of land-use change and the implications of spatial distribution of one land use in relation to others.

Challenges to disaggregating SDG trade-offs in peri-urban land use planning

A reinterpretation of the fieldwork data summarised in "Box 1: Fieldwork data" provided us with valuable insights into SDG trade-offs. The expansion of urban land-use and infrastructure into peri-urban areas may contribute to the goals of boosting employment and GDP (↑SDG 8.5—Decent work and economic growth), affordable housing and public services (↑SDG 11.1—Sustainable cities) and reducing health risks to urban residents from air pollution by displacing polluting industries out of city centres (↑SDG 3.9—Good health and well-being). However, there may be other trade-offs around the impact of the displacement of peri-urban agriculture on other aspects of the sustainability of urban food systems (SDG 2.4) and the disruption of the livelihoods of peri-urban farmers (SDG 8.5). This may contribute to more precarious conditions for migrants displaced from re-developed peri-urban areas

(SDG 10—inequality) and the siting of polluting industries near peri-urban agriculture may also put urban consumers at risk from contaminated foods (SDG 2.1). In addition, as vegetable production land is displaced in one area, nearby agricultural lands are often converted from corn, oilseed or other crops to intensive vegetable cultivation by migrant farmers as they seek to rebuild their livelihoods renting new lands from local farmers elsewhere. This implies that any large-scale land-use change in a peri-urban context is likely to have multiple impacts on different stakeholders, each with different implications for various SDGs. An understanding of these implications could greatly improve efforts to reduce trade-offs between SDG strategies, but the current information and planning tools utilised are not able to support such processes.

While data on agricultural production and area under cultivation are disaggregated to some extent in government statistics (city-wide or district-wise and by certain crops or categories of crop), the actual spatial distribution of different types of agriculture is very difficult to determine, especially in highly heterogeneous, rapidly changing peri-urban contexts. Ecosystem service mapping methods typically use only one category for agricultural land (Costanza et al. 2014, 1997; Jiang 2017; Long et al. 2014; Wu et al. 2013; Xie et al. 2017; Zhou et al. 2014) and Wuhan's master plan and provincial land-use maps do not distinguish different cropping systems (Kong et al. 2014; Zheng et al. 2018). This makes it impossible to interpret the implications of displacing different groups engaged in different types of agricultural activity (e.g. migrant vegetable farmers vs local mixed crop farmers) because these differences are simply not visible in the data. It also means that changes in the proximity of different types of agriculture to potential pollution sources such as industrial land use are not taken into account. For instance, placing intensive leafy vegetable production near the polluting industry may have a different impact on urban food safety than would the placing of oilseed, maize or root vegetable production in the same area.

Case study: developing a web-based tool to reveal SDG trade-offs associated with urban land-use planning in Wuhan

Our approach addresses these challenges in two ways. First, we have developed a flexible tool to generate fine-grained land-use maps which can disaggregate different types of urban and agricultural land-uses. Second, we have designed a method for integrating assumptions about the impacts of land-use change on a definable set of outcomes for different stakeholders with analysis of the land-use maps to visualize the complex trade-offs associated with different scenarios of land-use change. We have created a prototype web-application,[4] combining field knowledge, government plans, and aerial imagery to create an interactive land-use visualization. The intention of this application is to support multi-stakeholder discussion concerning SDG trade-offs related to urbanisation and urban planning. The following two sections describe (1) the development of the mapping tool; (2) design of the trade-off analysis function.

Development of the land-use mapping function

The application allows for an automated process of land-use classification, giving users the ability to create bespoke datasets by annotating tiled regions with user-defined class labels, such as 'rice paddy' or 'fish pond'.[5] Such a dataset can then be used to train a land-use classifier, which can be used to classify a user-defined region of interest. Classifications are then fed back into the application for visualization, and this process can be iterated to improve the classification. Further, if the user has access to high-resolution aerial imagery from multiple time periods, a time series of land-use changes can be constructed, providing information on the mutation of classes, e.g. the changing of agricultural land to industrial or from one type of agriculture to another. This system is hosted as a web-application, increasing accessibility to promote collaboration and crowdsourcing for example, by allowing multiple users to create training data, validate land-use visualizations qualitatively, and manually correct any errors.

During an initial proof-of-concept stage, the classification technique was tested using satellite imagery obtained through Google Maps API. Because the web-application was intended to be a widely accessible tool the decision was made to try to rely as much as possible on freely available data. We explored the potential to use freely available multispectral imagery (which is the standard source for land-use classification) such as Landsat or Sentinel. However, the resolution of this type of imagery, being usually 10–30 m, was not fine enough to reveal the details required for the classification we were attempting. We also approached several private satellite imagery companies who were each unable to provide imagery of a suitable resolution to cover our area of interest. Neither did we find any contemporary applications that could provide the necessary interactivity, imagery resolution or coverage for our purposes. Therefore, for the first stage of development, we relied on Google Maps API satellite imagery sourced from Maxar Technologies and CNES/Airbus as it currently offers unparalleled resolution

---

[4] https://ssrp-web-application.herokuapp.com/.

[5] See web-application website.

Fig. 1 Left: aerial image of the Veg-M class (Intensive vegetable cultivation by migrants), distinguished by the migrant huts (highlighted in red) at the bottom of the image. Right: Aerial image of the Veg-L class (Intensive vegetable cultivation by locals), distinguished by lack of migrant huts. Satellite Image: Google, Maxar Technologies

and coverage of the Wuhan area, allowing for classification at a very fine level. Due to this, it was possible to include the Veg-M/Veg-L classes (see below for further explanation) which would otherwise have been indistinguishable due to their very slight differences (see Fig. 1).

Following the successful testing of the land-use classifier, the web-application was re-designed in collaboration with a professional web-developer[6] with the aim of enhancing user interactivity and making the software fully extendable and modifiable for future applications. The most recent step was to redesign the process for obtaining satellite imagery data to overcome the increasing limitations placed on access to Google Maps data and to enable the user to include imagery from specific and multiple time periods from any source they have access to.[7] Reliance on freely available imagery from Google Maps API presented some additional challenges in the first stage of development. The most significant of these was that the imagery was not consistently from a particular point in time. In addition, the mismatch between the imagery viewed through the web-application for the purpose of labelling training data versus the imagery used to train the classifier meant that there were unavoidable discrepancies between the labels and the actual images. Realising that immediate improvements could be gained by access to a time-consistent data-source we redesigned the web-application to allow satellite imagery data (obtained from Google Earth Pro, which does allow for downloading time-consistent imagery for multiple dates) to be manually uploaded as jpeg or png files along with geo-location metadata. These are then converted within the web-application to the correct format and presented in the web-application interface for users to interact with. This imagery can be viewed in the

web-application allowing users to produce labelled training data sets for each year directly in the web-application by viewing the same imagery that will be analysed by the classifier. Output layers from the deep learning classifier can be viewed as overlays on the satellite imagery and manually corrected directly in the web-application interface.

This modification is now in the testing phase and one of the next steps for development is to explore the gains in accuracy obtained. The accuracy of the classifier will depend on the quality of the imagery, the design of the classification scheme and the appropriateness of the labelled training data. This means that the classification accuracy will vary with each different application of the mapping tool. Therefore, in future versions of the web-application, it will be important to integrate a measure of accuracy alongside the means for users to update classification schemes and training datasets to improve accuracy.

A central advantage of this approach is its usability. It allows anyone to upload imagery downloaded from free sources, such as Google Earth Pro, for any part of the globe and for multiple specified dates (depending on availability). These images can then be used directly to create interactive maps and models through our web-application without the need for any intermediate stages of complicated processing which are required for use in professional GIS applications. This is key to making the web-application accessible to non-expert users. Further, while the resulting maps will not provide as high location accuracy as other methods might, their purpose does not require such accuracy as they are not intended as tools for directly designing masterplans or neighbourhood land-use plans. Rather they are intended to support discussion about the land-use changes they reveal which can then influence the use of other tools in master planning and other planning processes.

Finally, the grid-based system of mapping allows for both a high level of usability in the interface for rapidly labelling training data and facilitates the creation and editing of

---

[6] James Robinson, web-developer, james@robinjam.net.

[7] This was part of the first phase of work for the project 'Inclusive Green Infrastructures for Urban Well-Being' funded by the British Academy (Award reference: UWB190102).

Table 1 Class distribution of annotated map tiles for Wuhan (1999–2017)

Land-use class	1999	2017	Totals
Intensive vegetable cultivation by locals	432	566	998
Intensive vegetable cultivation by migrants	291	360	651
Industrial	0	1446	1446
Urban	209	1287	1496
Background	4696	1793	6489
Oilseed (other)	659	754	1413
Rice paddy	370	394	764
Fish pond	283	1352	1635
Open-field vegetable/grain rotations	72	547	619
Water	411	3776	4187
Totals	7423	12,275	19,698

land-use layers for the modelling function. It also supports a classification scheme focused more on land-*use* rather than land-*cover*. Conventional methods tend to focus on a small number of land-cover types such as built-up area, plantation, waterbody, agricultural land, pastureland (e.g. Halefom et al. 2018). Land-use, on the other hand, is "the human employment of a land-cover type" (Malczewski 2004, p. 4) and includes aspects of how the land is made use of in people's

lives and livelihoods. Using a classification method that captures more of the contextual information that is physically manifested in a portion of the landscape such as the patterns and arrangements of fields and buildings, we are able to come closer to a classification of land-uses that goes beyond simply distinguishing between concrete and different types of vegetation cover and provides a simple and intuitive means of creating classification schemes and labelling training data.

For the Wuhan case study, we used the application to create a dataset of ten land-use classes covering the years 1999 and 2017 using satellite imagery obtained through Google Earth Pro, sourced from Maxar Technologies and CNES/Airbus. Land-use classes were as follows: urban, industrial, intensive vegetable cultivation by locals (Veg-L), intensive vegetable cultivation by migrants (Veg-M), oilseed (other), rice paddy, fish pond, open-field vegetable/grain rotations, water, and background (anything not deemed to be of interest). Veg-M classifies intensive vegetable production by migrant farmers, identified by the presence of single houses on the edges of fields. Veg-L classifies intensive vegetable production by local farmers who live in clusters of village housing, hence the absence of huts among fields. As discussed in the box above, this distinction is an important step in disaggregating the impacts of land-use change on
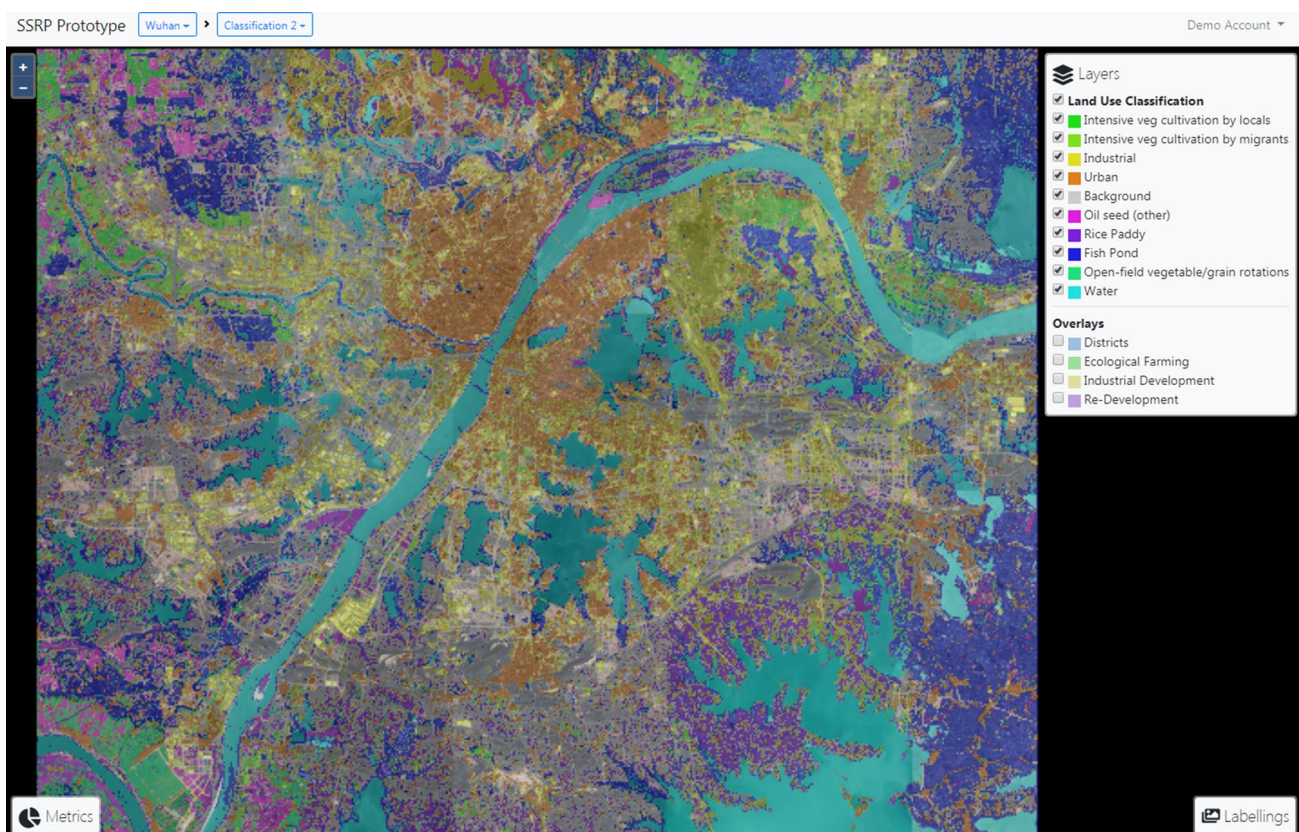
Fig. 2 Citywide map showing CNN generated land-use classification for 2017. Satellite Image: Google, Maxar Technologies and CNES/Airbus

different stakeholders. Open-field vegetable/grain rotations indicate intensive monocropping of vegetables (usually root or cabbage crops) in rotation with other staple crops such as maize while oilseed (other) indicates extensive cultivation of oilseed and other cash crops in larger fields.

In total, 19,698 ($256 \times 256 \times 3$ pixel) map tiles were annotated using the system at a resolution of 0.6 m/pixel. Separate training datasets were created for each year and the number of annotated tiles for each year and land-use class is shown in Table 1. Training data were labelled to reflect the distribution of land-use classes each year and the colour variations within the imagery for a single year. The distribution of annotated map tiles reflects the lack of full coverage of satellite imagery for 1999 and the changing distribution of land-use classes between the 2 years.

The training datasets were downloaded from the web-application and split into training, validation and testing sets with 70%, 20%, and 10% of the data, respectively. The classification technique used was a convolutional neural network (CNN), specifically, a variant known as a fully convolutional network (FCN), a modification on the classic CNN which removes the fully connected layers (Long et al. 2015). Next, the trained FCN was used to classify the imagery for the entire dataset covering the Wuhan area of interest (30.7559984583217° N, 113.941955566406° E and 30.237713497892° N, 114.700012207031° E) in which there was full coverage for 2017 and partial coverage for 1999. At the maximum zoom level, this area contained 242,767 $256 \times 256 \times 3$ pixel tiles for 2017 and 27,223 for 1999. Finally, the results were transferred to the web-application (see Fig. 2).

Design of the SDG trade-off analysis function

The second feature of the web-application is the SDG trade-off analysis function. Instead of a comprehensive model of land-use change trade-offs, this was designed to be an interactive 'thinking tool' that could support stakeholder engagement through a collaborative process of model design in which the central goal was shared learning. The value of this *procedural* approach to rationality in planning with GIS is in the way it leads "the user to think spatially" and "facilitate[s] social interaction and discourse in the pursuit of collective goals." (Malczewski 2004, p. 6). Our purpose was to enable users to highlight the trade-offs associated with land-use change between different outcomes for different stakeholders and to relate these directly to SDGs. Our approach does not directly compare the trade-offs between action to promote one SDG vs one or more other SDGs because this would obscure the multiple impacts of different types of land-use change on different aspects of various SDGs. Rather, we highlight the impact of a complex pattern of land-use change for multiple trade-offs between different

outcomes for different stakeholders across several SDGs. By focusing on the impacts of types of land-use change (e.g. the redevelopment of an area of intensive vegetable production by migrants into industrial land-use), we are able to explicitly recognise not only the direct impacts of the loss of one type of land-use vs the benefits of gaining another, but also the range of associated impacts of the change process on different stakeholders (e.g. displacement of people vs compensation arrangements for the loss of land and housing) along with any observable or assumed knock-on effects and changes in the proximity of one land-use to another.

To perform the analysis, a selection of categories of land-use change is scored for their impacts on a range of stakeholder-specific outcomes which are each associated with a particular SDG. In the web-application interface, the user can specify which types of land-use change they want to include in the model and write a set of simple functions that will compare the land-use classes from two specified time periods and produce a new labelled layer of land-use change classifications (see Fig. 3 for examples). These functions can also include changes in proximity to other types of land-use class, such as proximity to industry. This allows the user to apply judgements informed by published datasets about the type of impact on different outcomes of such proximity changes. It will also highlight the need for more data on particular aspects of spatial relationships between different land-uses. For example, if a land-use change to industry occurs adjacent to remaining vegetable production this could have a potentially negative impact on food safety through the increased risk of contamination of crops by industrial pollution. Where data on these risks exist, it can be incorporated into the model and gaps in data can also be identified. This land-use change labelling function could also be developed further to allow data from other layers to be incorporated, for example, if the user wanted to take into account the influence of particular land-use policies such as pollution controls or agricultural support policies which apply to particular geographical areas and not others or to include data from ecosystem services mapping.

Next, a set of metrics is designed by specifying a list of outcomes that are influenced by these land-use changes. These metrics are written as expressions using the different types of land-use change as inputs and can, therefore, be made as simple or complex as necessary. The following screenshot (Fig. 4) shows how the scoring expressions are constructed. Each variable refers to a specific type of land-use change and inputs the area of that land-use change as a negative or positive contribution. Multipliers can be included if desired. For example, data on crop yields and per head vegetable consumption could be used to calculate the impact of land-use change on the food system in terms of loss of capacity to meet daily per head consumption. Similarly, one could use field data to estimate the number of

Fig. 3 Land-use change labelling rules. Each rule is associated with a Boolean expression; when this expression evaluates to true the corresponding label is applied. Evaluation of these expressions is implemented using the Dentaku rubygem (https://github.com/rubysolo/dentaku). Variable names such as 'veg_intensive_l' refer to land-use classes and are set by the user. In this case, 'veg_intensive_l' is the variable name for 'Intensive vegetable cultivation by locals'. The variables 'before' and 'after' refer to the land-use classification at time 0 and time 1 of the land-use change which are set by the user when running the function. The expression 'is_nearby' measures proximity to a specified land-use within a set number of tiles, in this case set to 5

migrant farming households per hectare and calculate the total number of migrant households displaced as a result of the land-use changes. In addition, a transformative negative impact on a particular group of stakeholders (e.g. loss of livelihoods of migrant farmers) may be weighted more highly to indicate greater significance to that group than an incremental loss of GDP would be to business and government stakeholders.

For the purpose of demonstration, we have devised the simplest possible scoring system which defines impacts as a simple positive or negative score:

- 0 = no impact,
- 1 = positive impact. For example,

  - the positive impact of compensation obtained by local farmers when fields are redeveloped for industry;
  - the positive impact of industrial development on urban employment opportunities.

- − 1 = negative impact. For example,

  - the negative impact of industry on clean air or water;
  - the negative impact of the loss of migrant farmers' livelihoods and assets due to the redevelopment of vegetable fields.

This scoring system is only illustrative in this case and merely provides an aggregate of the area of land-use

Fig. 4 Land-use change impact metrics. Users construct expressions from variables representing the area covered by each type of land-use change (e.g. the value of variable 'vim_urb_f' is the number of tiles with that label). Evaluation of these expressions is implemented using the Dentaku rubygem (Ibid). In this example, the land-use change variable 'vim_urb_f' refers to all tiles which, at time 0 where clas-sified 'Intensive vegetable cultivation by migrants' (vim) and at time 1 were classified 'Urban' (urb) not in proximity to Industry (hence 'urb_f'). 'vim_urb_t' refers to the change from vim to urb in which the proximity to Industry of tiles now classified 'Urban' has changed from false to true (hence 'urb_t')

change that is considered to contribute to each outcome. Nevertheless, the web-application provides the flexibility to develop a more complex scoring system to reflect a more nuanced approach to the type of impacts experienced by different groups. In the demonstration model, the sum of these weighted scores represents the total impact of a pattern of land-use change on each outcome which can then be visualised on a graph. This provides a simple and intuitively understandable visualisation of a range of possible impacts of land-use changes on different groups alongside a spatial representation of land-use changes. This can then form the first step in a participatory process of engaging stakeholders to expand the set of relevant outcomes and collaboratively build a more complex model of the impacts of land-use change on those outcomes. Through a bottom-up approach, it allows users to bring in a range of data from multiple sources alongside their own subjective experience in a transparent way and prompts researchers and stakeholders alike to make explicit their assumptions about which outcomes to include and why, as well as how to score them in relation to particular types of land-use change. Thus, the process begins with a highly subjective and simplistic model, the
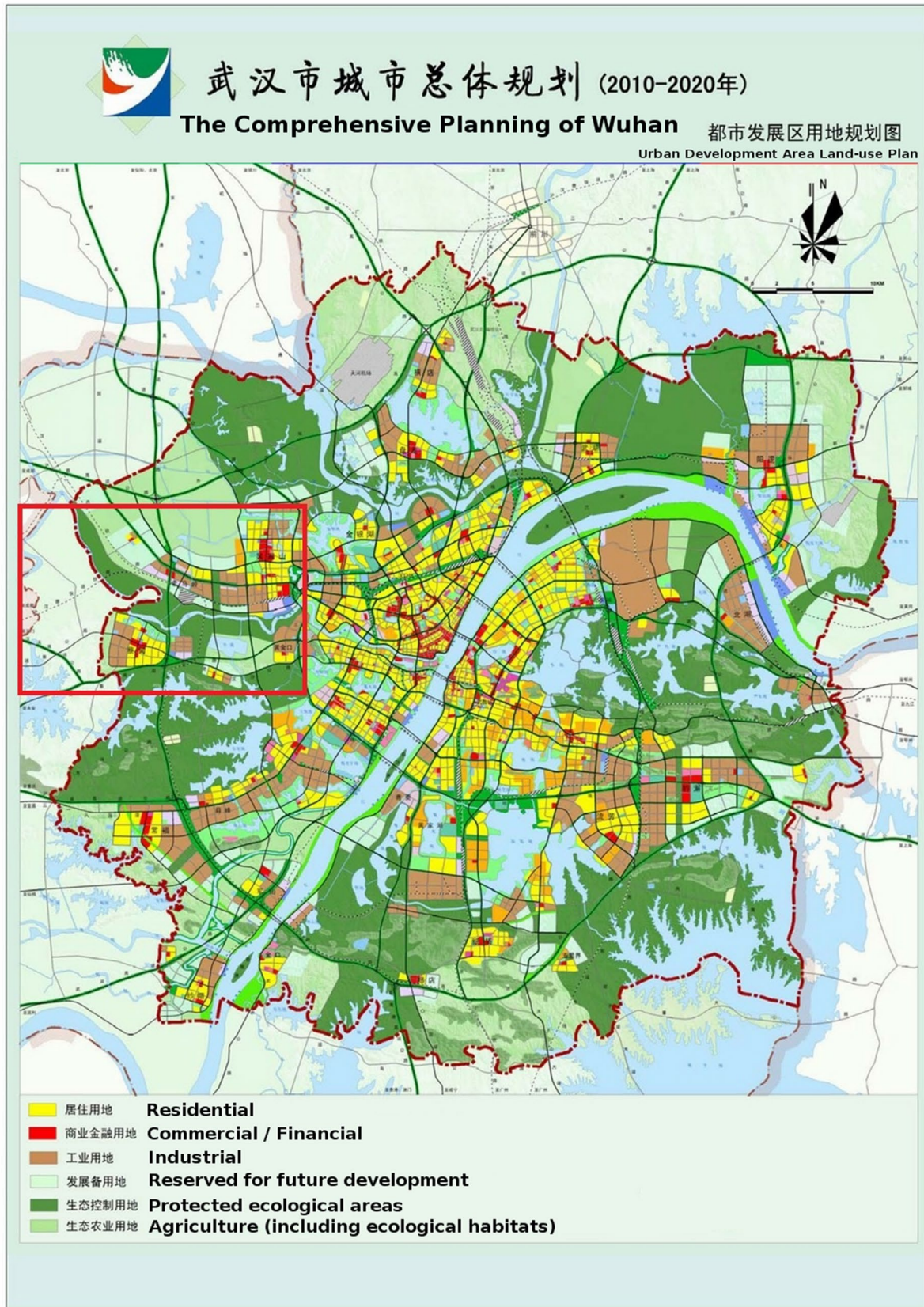
Fig. 5 Wuhan Masterplan (from Wuhan Land Resources and Planning Bureau https://gtghj.wuhan.gov.cn/) showing area of interest highlighted by a red outline. Key land-use classes are translated in the map key
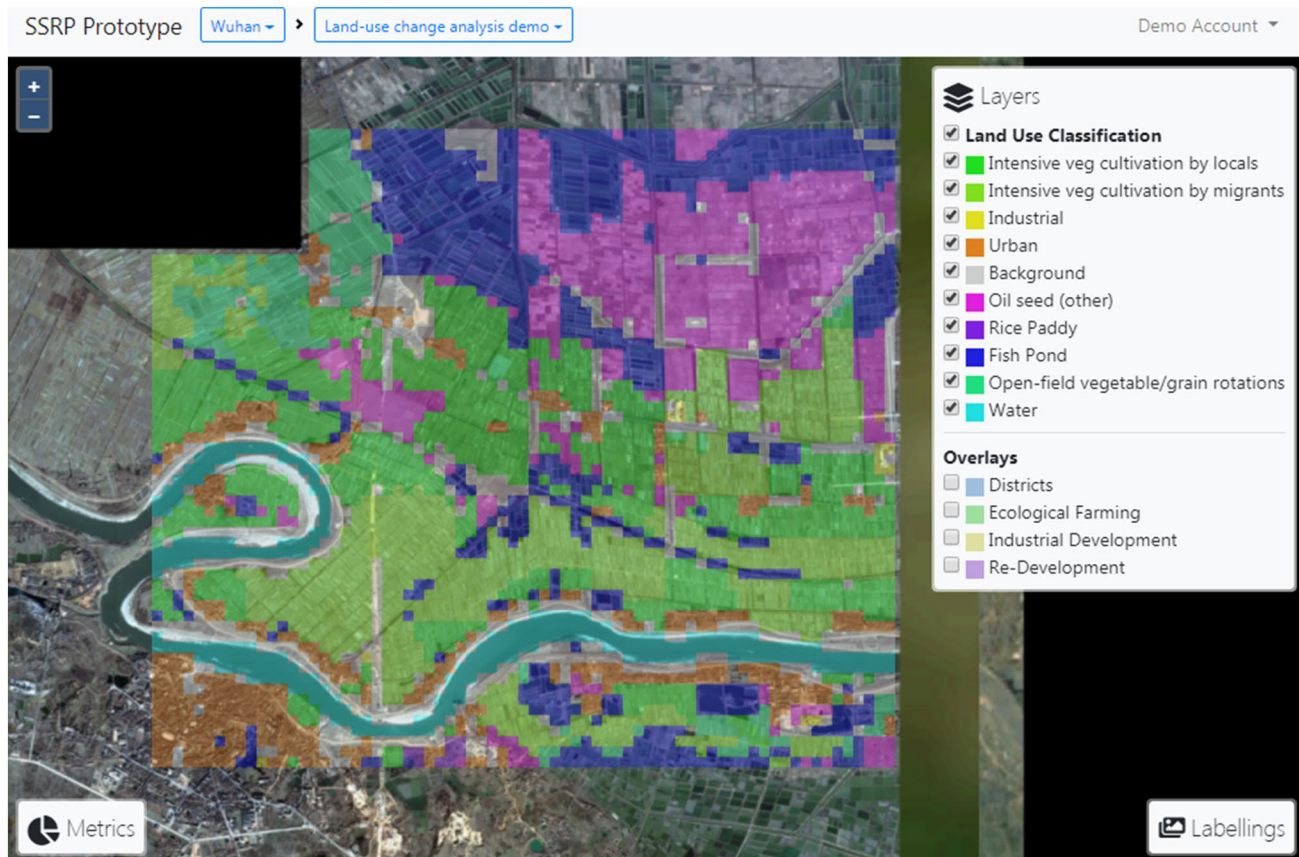
Fig. 6 Land-use pattern in Dongxihu district, 1999. Satellite Image: Google, Maxar Technologies and CNES/Airbus

purpose of which is to raise questions and provoke objections to develop the model further to reflect broader and more nuanced understandings of the dynamic peri-urban context. The broader goal of this process is to support shared learning about the diversity of issues involved in planning decisions and to provide an opportunity for marginalised interests to be recognised.

Worked example of SDG trade-off scenario analysis

We explore the case of Dongxihu district in Wuhan to demonstrate how the web-application might be used to reveal and communicate the hidden trade-offs between SDGs involved in planning decisions about the siting of industrial and urban development in relation to peri-urban food systems. We first outline the recent process of urban expansion in Dongxihu and then describe how the web-application could be used to analyse and visualise the trade-offs associated with this pattern of land-use change.

Dongxihu district is one of Wuhan's six outer districts and contains a sprawling urban conurbation surrounded by a large area of agricultural lands occupied by a mixture villages and state farms. The district has seen a steady decline

in the percentage of land under cultivation as large areas of land have been converted to industrial, commercial and residential uses as well as road infrastructure. Between 1999 and 2017 much of the agricultural land closest to the town centre has been completely replaced by urban land-use. The 2010–2020 Masterplan for urban development in Wuhan (Fig. 5) shows the extent of urban land uses expected by 2020. The red box outlines an area of west Wuhan containing the southern section of Dongxihu district where redevelopment has taken place and the northern section of Caidian district below that.

Using the web-application we can compare a past land-use pattern with the present pattern of land-use to determine the land-use change that has occurred as a result of industrial development. Figure 6 shows a screenshot of the web-application displaying the pattern of land-use in the same section of west Wuhan in 1999 while Fig. 7 displays land-use in 2017. For the purpose of this illustration, the land-use class labels have been edited by hand to ensure the highest possible accuracy. When performing this kind of analysis on the city region such corrections would be unrealistic to perform because of the much larger number of map tiles that would have to be examined. This means that for city
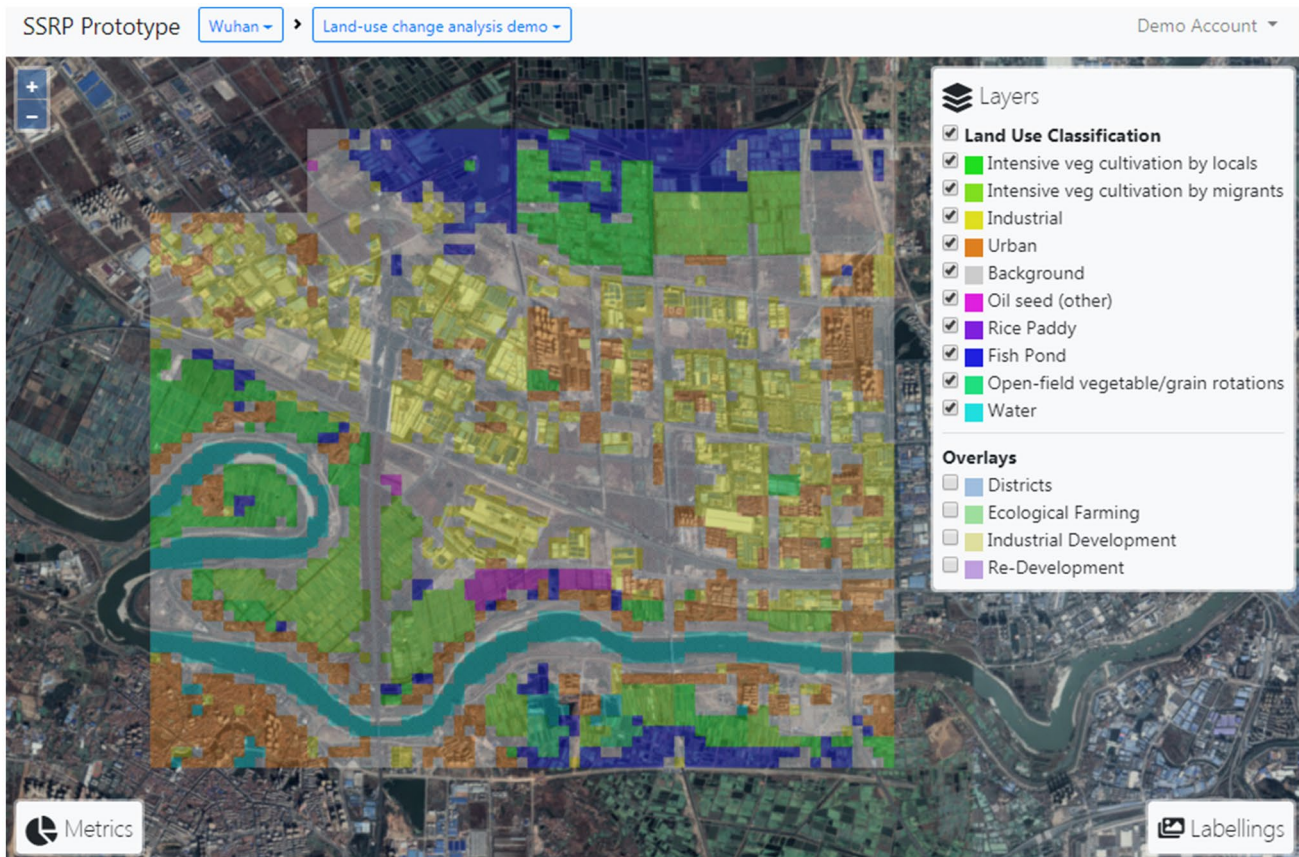
Fig. 7 Land-use pattern in Dongxihu district, 2017. Satellite Image: Google, Maxar Technologies and CNES/Airbus

region analyses, a margin of error needs to be assumed and we will seek to incorporate into a future version a means of estimating that error margin. In these maps, the distribution of different types of agriculture can be clearly seen including oilseed (other), fish ponds, and the two types of intensive vegetable production (migrant vegetable production in dark green and local vegetable production in lighter green). Orange areas indicate general urban land use (including residential and commercial) while yellow areas indicate industrial land use. Background land-use is indicated in grey and includes barren land, non-agricultural vegetation and roadways. In this case, comparison of the two maps shows that virtually all of the land now occupied by industry or cleared for redevelopment was, for several years prior to its urbanisation, given over to the intensive cultivation of vegetables and much of it by migrant farmers.

To begin analysing the impacts of this land-use change, the first step would be to work with stakeholders to define a list of outcomes (including reference to quantitative and qualitative datasets as appropriate) along with the specific type of land-use change that has the most significant impact on that outcome (see Table 2 as an example). For illustrative purposes, we have selected the set of outcomes to

demonstrate the range of perspectives from different stakeholders and the priorities they might be expected to assign to different aspects of SDGs. These outcomes reflect the multiple dimensions of food security alongside the economic goals of urban development. Where stakeholders would be expected to have different perspectives on the same category of outcome, we separate these to make these differences explicit. GDP growth (SDG 8) and urban food supply and safety (SDG 2) may be expected to reflect the interests of municipal policy-makers to boost the urban economy and secure vegetable supplies to the city while provincial/national food supply and safety (SDG 2) may reflect the priority of the provincial government to secure staple food supplies. The interests of poorer tenant farmers might be most clearly reflected in the outcome 'Livelihoods for the poor' which we have divided into two types of outcome, the negative outcome of displacement of migrant farmers and the positive outcome of opportunities for migrant farmers to set up profitable peri-urban farming livelihoods. Each outcome is important to different groups of stakeholders and we have made some illustrative assumptions, informed by the case study data, about how each group would score the outcomes of greatest priority to them. In practice, we would expect

Table 2 Stakeholder-specific outcomes and key land-use changes

SDG	SDG title	Target	Outcome	Description	Key land-use change
2	Zero hunger	1	Urban food supply	Supply of fresh vegetables for urban markets	Peri-urban vegetable production
2	Zero hunger	1	Urban food safety	Risk of contaminants entering the food chain	Proximity to sources of pollution (i.e. industrial land-use)
2	Zero hunger	1	Provincial/national food supply	Staple foodstuffs for national markets	Other types of agriculture, location less important
2	Zero hunger	1	Provincial/national food safety	Risk of contaminants entering the food chain	Proximity to sources of pollution (i.e. industrial land-use)
8	Decent work and economic growth	2	GDP growth	Increase in the area of industrial land contributes to increased GDP	Replacement of any land-use with industrial or loss of industrial to any other land-use
10	Reduced inequalities	7	Livelihoods for the poor (opportunities for migrant farmers)	Opportunities for rural households to migrate (bringing children and elderly relatives) to peri-urban areas to establish decent agri-livelihoods and gain access to urban schools. More stable than the separation of families to migrate for informal urban employment	Conversion of any other agriculture to 'intensive vegetable cultivation by migrants'
10	Reduced inequalities	7	Livelihoods for the poor (displacement of migrant farmers)	Displacement of households incurring the loss of homes, lands and livelihood as a result of redevelopment	Replacement of 'intensive vegetable cultivation by migrants' by urban, industrial or background

the list of outcomes and scores to be determined through an in-depth participatory process which also draws on a range of other datasets; perhaps in similar ways, as described in Multi-Criteria Mapping (MCM) (Burgess et al. 2007; Stirling and Mayer 2001), Multi-Criteria Decision Analysis (MCDA) approaches (Greco et al. 2016; Langemeyer et al. 2016; Linkov et al. 2006; Mendoza and Martins 2006) and participatory GIS and planning practices (Brown et al. 2018; Bugs et al. 2010; Kahila and Kyttä 2009; Malczewski 2004; Talen 2000).

To illustrate how different types of land-use change would be scored against outcomes, Table 3 shows the scores for changes from or to Veg-M and industrial. The 'Land-use change' row describes the type of change in relation to each of the two classes. The row 'Proximity to industrial land-use after change' indicates whether the resulting land-use has become adjacent to industrial land-use (TRUE or FALSE).

Using these impact scores, multiple scenarios of land-use change can be compared according to the area of each type of land-use change involved and the implications this has for the total impact score on each outcome. In an urban planning situation, the same analysis could be done using several alternative scenarios of future land-use and policy. This functionality to create hypothetical scenarios is already built into the web-application in a basic form as labelled layers that can be edited by hand and used as inputs into the trade-off model. However, further development of this function would aim to provide greater functionality and usability so as to explore the implications of alternative planning strategies.

The following screenshots (Figs. 8, 9) help to illustrate the way in which the web-application can facilitate engagement around land-use planning decisions. The first map shows the pattern of land-use change that has occurred between 1999 and 2017 in a portion of Dongxihu district and enables the user to interact with the map to isolate particular types of land-use change to see clearly where they have taken place in relation to their wider spatial context. It shows graphically the huge amount of land-use change that has occurred and in particular the relative scale of the loss of vegetable production land. This type of map provides a focal point for engagement with stakeholders on the difference between expected or planned land-use change and the reality on the ground and would provide a useful step towards the co-design of trade-off models as people have the opportunity to look at the most significant types of changes that have taken place and their spatial distribution.

Once a trade-off model has been designed it can be run on the entire labelled area or any part of it to produce a graph of the metrics as shown in Fig. 9. In this screenshot, the types of land-use change are ranked by percentage of the total area selected. The total impact scores for the selected area are presented in a graph which shows at a glance an

Table 3 Example of simple impact scores. Scoring the expected impact of land-use change on SDG-related outcomes for different stakeholders. In practice this would be based on stakeholder work- shops, field research, published data, statistical data etc. In this exam- ple: $+1$ = positive impact, -1 = negative impact, 0 = no impact

Land-use class	Intensive vegetable cultivation by migrants				Industrial	
Land-use change	Loss to any land-use	Gain from other agri-land-use		Remain	Loss	Gain
		False	True			
Proximity to industrial land-use after change	n/a	False	True	From false to true	n/a	n/a
SDG 2.1—urban food supply—i.e. vegetables for urban markets	-1	1	1	0	0	0
SDG 2.1—urban food safety—i.e. risk of contaminants entering food chain	0	0	-1	-1	0	0
SDG 2.1—provincial/national food supply—i.e. grains for national markets	0	-1	-1	0	0	0
SDG 2.1—provincial/national food safety	0	0	0	0	0	0
SDG 8.2—GDP growth—e.g. from new industrial production	0	0	0	0	-1	1
SDG 10.7—livelihoods for the poor (opportunities)—i.e. opportunities for rural households to migrate to decent agri-livelihoods vs separation of families to migrate for informal urban employment	0	1	1	0	0	0
SDG 10.7—livelihoods for the poor (displacement)—i.e. displacement of peri-urban migrant farmers	-1	0	0	0	0	0

indication of the positive and negative impacts of the pattern of land-use change.

The resulting graph (Fig. 9) highlights that the positive impacts on GDP growth (SDG 8.2) associated with large-scale industrial development are traded off against a whole set of negative impacts on urban and provincial food supplies and food safety (SDG 2.1) as well as a negative impacts on livelihoods for the poor in terms of the displacement of migrant farmers which are only partly offset by the creation of new opportunities. Clearly, the scale at which this analysis is performed will significantly influence the results obtained and the web-application can be used to highlight this issue as the metrics can be run on the entire area of interest or any part of it selected by the user. It is, therefore, vital that the issue of scale is carefully considered as a central issue throughout any stakeholder engagement process using the web-application.

Supporting stakeholder engagement in planning contexts

Using and developing these visualisations in a group setting with a range of stakeholders would help to ground discussions about land-use policy and planning by providing a means of collaboratively thinking through the diversity of outcomes and impacts of land-use change and making explicit the assumptions made by different stakeholders. The first context in which the web-application has been field-tested is in a workshop in Wuhan. This workshop included policy/planning officials and academic researchers and included a field visit to peri-urban Wuhan. The workshop was used to demonstrate the functionality of the web-application and trial its use to facilitate discussion on the impacts of historical land-use changes and the priorities for future urban planning strategies. Reflections on this workshop by participants will be incorporated into the continuing development of the web-application and the design of protocols for its use in stakeholder engagement processes for both planning and research as the project continues.

In the planning context in China, this tool could be used to facilitate multi-stakeholder dialogues within the current masterplan preparation process at the stage in which land-use status is analysed. In this case, it could be used to bring together a range of spatial and quantitative data alongside the experience and insights of diverse stakeholders to inform the choice of priorities and tools for detailed analysis of land-use suitability as well as feeding into the design of Strategic Environmental Assessments (see Tao et al. 2007 for more on China's land-use planning system) to help steer planning processes towards the goal of achieving China's 'ecological civilisation' (Marinelli 2018).

Conclusion

In this paper, we have described a novel approach to analysing the complex trade-offs between SDGs associated with peri-urban land-use change. Our approach combines high-resolution top-down remote sensing data with bottom-up knowledge and diverse stakeholder perspectives to disaggregate the impacts of large-scale land-use change on different groups and in relation to multiple SDGs. Our demonstration
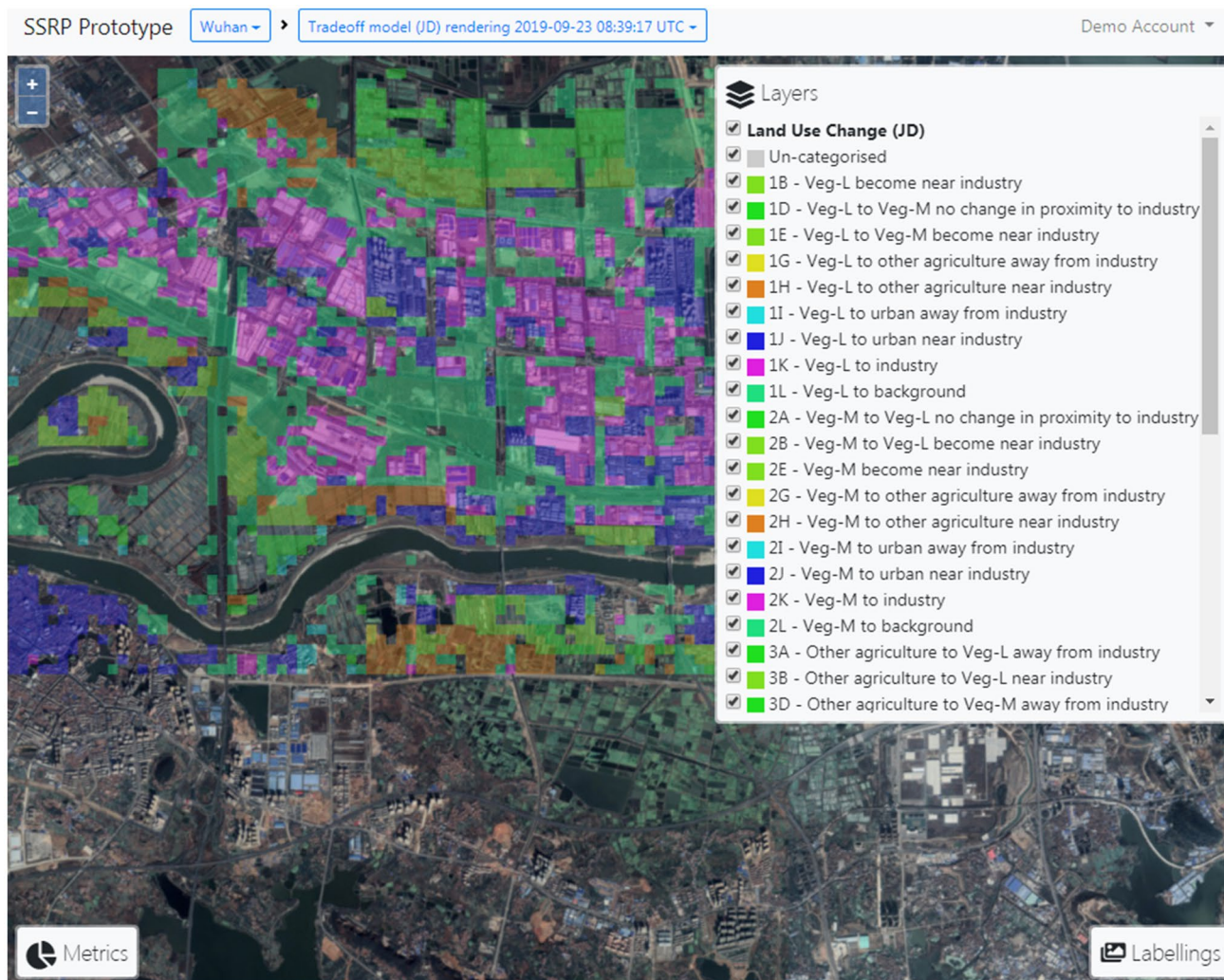
Fig. 8 Land-use change map for Dongxihu district, 1999–2017. Satellite Image: Google, Maxar Technologies and CNES/Airbus

of the prototype web-application through the Wuhan case study shows that it is capable of revealing important differences in land-use classes and their proximity to each other which are significant for SDG interactions but are obscured in formal data and current land-use mapping approaches. It allows for an integrated analysis of the changing distribution of land-uses going beyond a simple cost–benefit analysis of the loss of one type of land-use versus the gain of another to reflect the diversity of outcomes for different stakeholders. We have described how the web-application could be used to support a dialogue between policy-makers and other stakeholders about how particular policies and development processes contribute to outcomes and what changes might be appropriate in particular contexts.

This is an approach that offers great promise for supporting more inclusive planning processes by providing a platform for stakeholders to contribute to analysis of the

potential impacts of planning decisions and explore the implications of alternative future scenarios through a process of shared learning. Used alongside existing participatory planning methods, GIS tools and ecosystem services mapping, our approach offers a powerful tool to reveal invisible trade-offs and foreground the perspectives of diverse stakeholders. Faced with a lack of fine-grained data on land-use distribution and agricultural statistics for rapidly urbanising contexts our web-application demonstrates what can be achieved with freely available satellite imagery to address this gap.

Having developed the current prototype web-application based on fieldwork insights, we have demonstrated its potential to make a significant contribution to enhancing our understanding of pathways to sustainability in rapid transition zones. The next steps are to co-develop the web-application with stakeholders in a number of geographical locations
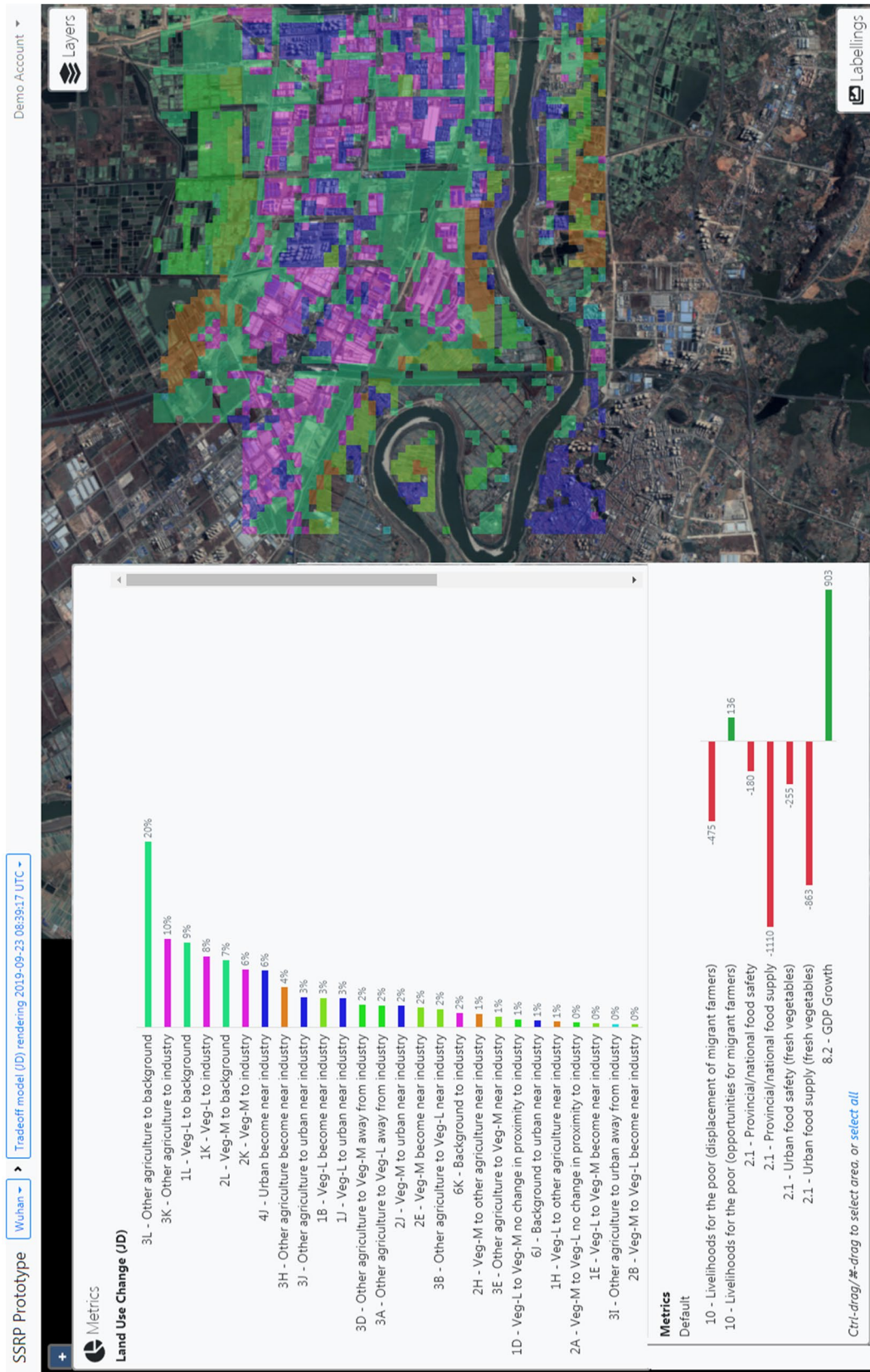
Fig. 9 Land-use change map and impact metrics for Dongxihu district, 1999–2017. Satellite Image: Google, Maxar Technologies and CNES/Airbus

and planning contexts to incorporate more functionality and interactivity and explore its usefulness in the planning process. The first phase of this work will include a program of co-design, research and learning exchanges with partners in Wuhan, China and Delhi, India. As our approach evolves this will also allow for a detailed comparison with other approaches to participatory planning and decision-making and provide shared learning on strategies for building synergies between SDGs.

References

Agrawal M, Singh B, Rajput M, Marshall F, Bell JNB (2003) Effect of air pollution on peri-urban agriculture: a case study. Environ Pollut 126:323–329. https://doi.org/10.1016/S0269-7491(03)00245-8

Bowen KJ, Cradock-Henry NA, Koch F, Patterson J, Häyhä T, Vogt J, Barbi F (2017) Implementing the "Sustainable Development Goals": towards addressing three key governance challenges—collective action, trade-offs, and accountability. Curr Opin Environ Sustain 26–27:90–96. https://doi.org/10.1016/j.cosust.2017.05.002

Brown G, Sanders S, Reed P (2018) Using public participatory mapping to inform general land use planning and zoning. Landsc Urban Plan 177:64–74. https://doi.org/10.1016/j.landurbplan.2018.04.011

Bugs G, Granell C, Fonts O, Huerta J, Painho M (2010) An assessment of public participation GIS and web 2.0 technologies in urban planning practice in Canela, Brazil. Cities 27:172–181. https://doi.org/10.1016/j.cities.2009.11.008

Burgess J, Stirling A, Clark J, Davies G, Eames M, Staley K, Williamson S (2007) Deliberative mapping: a novel analytic-deliberative methodology to support contested science-policy decisions. Public Underst Sci 16:299–322. https://doi.org/10.1177/0963662507077510

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Glob Environ Chang 26:152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Baldi A et al (2015) The IPBES conceptual framework—connecting nature and people. Curr Opin Environ Sustain 14:1–16

Dolley J (2017) Sustainability, resilience and governance of an urban food system: a case study of peri-urban Wuhan (Doctoral thesis (PhD)). University of Sussex, Brighton [Online]. https://sro.sussex.ac.uk/66462/

Ericksen PJ (2008a) What is the vulnerability of a food system to global environmental change?. Ecol Soc 13:14–31

Ericksen PJ (2008b) Conceptualizing food systems for global environmental change research. Glob Environ Chang 18:234–245. https://doi.org/10.1016/j.gloenvcha.2007.09.002

Greco S, Figueira J, Ehrgott M (eds) (2016) Multiple criteria decision analysis. Springer, New York

Gu S (2009) The emergence and development of the vegetable sector in China. Ind Innov 16:499–524

Halefom A, Teshome A, Sisay E, Ahmad I (2018) Dynamics of land use and land cover change using remote sensing and GIS: a case study of Debre Tabor Town, South Gondar, Ethiopia. J Geogr Inf Syst 10:165–174. https://doi.org/10.4236/jgis.2018.102008

Hu W, Chen Y, Huang B, Niedermann S (2014) Health risk assessment of heavy metals in soils and vegetables from a typical greenhouse vegetable production system in China. Hum Ecol Risk Assess Int J 20:1264–1280. https://doi.org/10.1080/10807039.2013.831267

Jiang W (2017) Ecosystem services research in China: a critical review. Ecosyst Serv 26:10–16. https://doi.org/10.1016/j.ecoser.2017.05.012

Kahila M, Kyttä M (2009) SoftGIS as a bridge-builder in collaborative urban planning. In: Geertman S, Stillwell J (eds) Planning support systems best practice and new methods. Springer Netherlands, Dordrecht, pp 389–411

Kong X, Liu Y, Liu X, Chen Y, Liu D (2014) Thematic maps for land consolidation planning in Hubei Province, China. J Maps 10:26–34. https://doi.org/10.1080/17445647.2013.847388

Langemeyer J, Gómez-Baggethun E, Haase D, Scheuer S, Elmqvist T (2016) Bridging the gap between ecosystem service assessments and land-use planning through Multi-Criteria Decision Analysis (MCDA). Environ Sci Policy 62:45–56. https://doi.org/10.1016/j.envsci.2016.02.013

Linkov I, Satterstrom FK, Kiker G, Batchelor C, Bridges T, Ferguson E (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. Environ Int 32:1072–1093. https://doi.org/10.1016/j.envint.2006.06.013

Long H, Liu Y, Hou X, Li T, Li Y (2014) Effects of land use transitions due to rapid urbanization on ecosystem services: implications for urban planning in the new developing area of China. Habitat Int 44:536–544. https://doi.org/10.1016/j.habitatint.2014.10.011

Long J, Shelhamer E., Darrell T (2015) Fully convolutional networks for semantic segmentation. In: Proceedings of the IEEE conference on computer vision and pattern recognition (CVPR), Boston, MA, pp 3431–3440

Luo Q, Zhang X, Li Z, Yang M, Lin Y (2018) The effects of China's ecological control line policy on ecosystem services: the case of Wuhan City. Ecol Ind 93:292–301. https://doi.org/10.1016/j.ecolind.2018.05.009

Malczewski J (2004) GIS-based land-use suitability analysis: a critical overview. Prog Plan 62:3–65

Marinelli M (2018) How to build a 'Beautiful China' in the Anthropocene. The political discourse and the intellectual debate on ecological civilization. J Chin Polit Sci 23:365–386. https://doi.org/10.1007/s11366-018-9538-7

Marshall F (2016) Recognizing sustainability frontiers in the peri-urban. South Asian Water Stud 5(3):98–102

Marshall F, Dolley J (2019) Transformative innovation in peri-urban Asia. Res Policy 48:983–992. https://doi.org/10.1016/j.respol.2018.10.007

Marshall F, Dolley J, Bisht R, Priya R, Waldman L, Amerasinghe P, Randhawa P (2018) Ecosystem services and poverty alleviation in urbanising contexts. In: Schreckenberg K, Mace G, Poudyal M (eds) Ecosystem services and poverty alleviation: trade-offs and governance (OPEN ACCESS), Routledge studies in ecosystem services. Routledge, London, pp 111–125

Marshall F, Randhawa P (2017) India's peri-urban frontier: rural-urban transformations and food security. IIED, London [online]. https://pubs.iied.org/10794IIED

Marshall F, Scharlemann J, Waldman L, Priya R, Punia M, Desai P, Amerasinghe P (2016) Risks and responses to urban futures: integrating peri-urban/urban synergies into urban development planning for enhanced ecosystem services benefits. ESPA Funded Project, University of Sussex, Brighton, UK. https://steps-centre.org/project/urban-futures

Marshall F, Waldman L, MacGregor H, Mehta L, Randhawa P (2009) On the edge of sustainability: perspectives on peri-urban dynamics (STEPS Working Paper No. 35). STEPS Centre, Brighton [online]. https://steps-centre.org/wp-content/uploads/Peri-urban-online-version.pdf

MEA (2005) Millennium ecosystem assessment, ecosystems and human wellbeing: synthesis. Millennium Ecosystem Assessment, Washington, DC

Mendoza GA, Martins H (2006) Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. For Ecol Manag 230:1–22. https://doi.org/10.1016/j.foreco.2006.03.023

Misselhorn A, Aggarwal P, Ericksen P, Gregory P, Horn-Phathanothai L, Ingram J, Wiebe K (2012) A vision for attaining food security. Curr Opin Environ Sustain 4:7–17. https://doi.org/10.1016/j.cosust.2012.01.008

Parnell S (2016) Defining a global urban development agenda. World Dev 78:529–540. https://doi.org/10.1016/j.worlddev.2015.10.028

Pascual U, Howe C (2018) Seeing the wood for the trees: exploring the evolution of frameworks of ecosystem services for human wellbeing. In: Schreckenberg K, Mace G, Poudyal M (eds) Ecosystem services and poverty alleviation: trade-offs and governance (OPEN ACCESS), Routledge studies in ecosystem services. Routledge, London, pp 3–21

Seto KC, Golden JS, Alberti M, Turner BL (2017) Sustainability in an urbanizing planet. Proc Natl Acad Sci 114:8935–8938. https://doi.org/10.1073/pnas.1606037114

Si Z, Scott S (2016) Approaching sustainable urban development in China through a food system planning lens (No. 2). Hungry Cities Report, Hungry Cities Partnership, Waterloo

Simon D (2008) Urban environments: issues on the peri-urban fringe. Annu Rev Environ Resour 33:167–185

Singh A, Sharma RK, Agarwal M, Marshall F (2010) Health risk assessment of heavy metals via dietary intake from the wastewater irrigated site of a dry tropical area of India. Food Chem Toxicol 48:611–619. https://doi.org/10.1016/j.fct.2009.11.041

Stirling A, Mayer S (2001) A novel approach to the appraisal of technological risk: a multicriteria mapping study of a genetically modified crop. Environ Plan C Gov Policy 19:529–555. https://doi.org/10.1068/c8s

Talen E (2000) Bottom-up GIS: a new tool for individual and group expression in participatory planning. J Am Plan Assoc 66:279–294

Tao T, Tan Z, He X (2007) Integrating environment into land-use planning through strategic environmental assessment in China: towards legal frameworks and operational procedures. Environ Impact Assess Rev 27:243–265. https://doi.org/10.1016/j.eiar.2006.10.002

WAB (2012) Wuhan Agriculture Bureau Report 2012: research report on Wuhan vegetable circulation costs 关于武汉市蔬菜流通运行成本的调研报告. Wuhan Bureau of Agriculture and Rural Affairs 武汉市农业农村局, Wuhan, China. http://nw.wuhan.gov.cn/

WAB Director (2012) Interview with a director at Wuhan Agriculture Bureau Markets Department (武汉市农业局市场处), Wuhan, China. Interviewed by Jonathan Dolley, 6 March 2012

WH (2017) Wuhan Statistical Yearbook 2017, Hubei Provincial Bureau of Statistics 湖北省统计局 (tjj.hubei.gov.cn)

WH (2010) Wuhan Statistical Yearbook 2010, Hubei Provincial Bureau of Statistics 湖北省统计局 (tjj.hubei.gov.cn)

Wu J, Xiang W-N, Zhao J (2014) Urban ecology in China: historical developments and future directions. Landsc Urban Plan 125:222–233. https://doi.org/10.1016/j.landurbplan.2014.02.010

Wu K, Ye X, Qi Z, Zhang H (2013) Impacts of land use/land cover change and socioeconomic development on regional ecosystem services: the case of fast-growing Hangzhou metropolitan area, China. Cities 31:276–284. https://doi.org/10.1016/j.cities.2012.08.003

Xie G, Zhang C, Zhen L, Zhang L (2017) Dynamic changes in the value of China's ecosystem services. Ecosyst Serv 26:146–154. https://doi.org/10.1016/j.ecoser.2017.06.010

Young J (2013) China's Hukou system: markets, migrants and institutional change. Palgrave Macmillan, UK

Zhang C, Yang Y, Li W, Zhang C, Zhang R, Mei Y, Liao X, Liu Y (2015) Spatial distribution and ecological risk assessment of trace metals in urban soils in Wuhan, central China. Environ Monit Assess 187:556–571. https://doi.org/10.1007/s10661-015-4762-5

Zheng W, Ke X, Zhou T, Yang B (2018) Trade-offs between cropland quality and ecosystem services of marginal compensated cropland—a case study in Wuhan, China. Ecol Indic. https://doi.org/10.1016/j.ecolind.2018.05.089

Zhou K, Liu Y, Tan R, Song Y (2014) Urban dynamics, landscape ecological security, and policy implications: a case study from the Wuhan area of central China. Cities 41:141–153. https://doi.org/10.1016/j.cities.2014.06.010