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Optimizing Peri-URban Ecosystems (PURE) to Re-couple Urban-Rural Symbiosis

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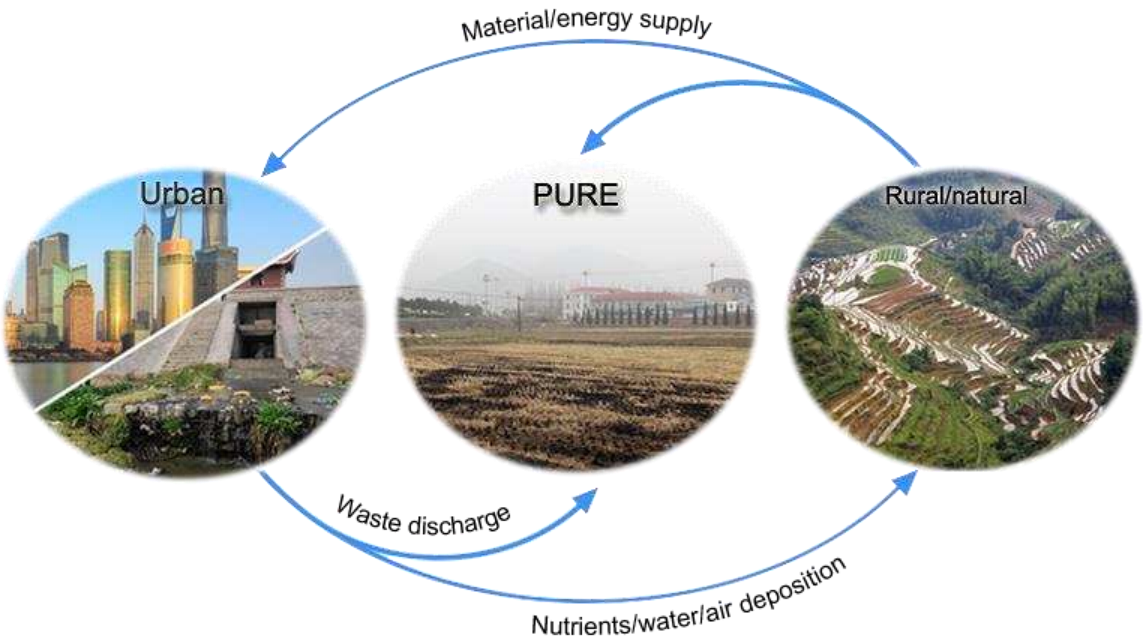
ABSTRACT

Globally, rapid urbanization, along with economic development, is dramatically changing the balance of biogeochemical cycles, impacting upon ecosystem services and impinging on United Nation global sustainability goals (inter alia: sustainable cities and communities; responsible consumption and production; good health and well-being; clean water and sanitation, and; to protect and conserve life on land and below water). A key feature of the urban ecosystems is that nutrient stocks, carbon (C), nitrogen (N) and phosphorus (P), are being enriched. Furthermore, urban ecosystems are highly engineered, biogeochemical cycling of nutrients within urban ecosystems is spatially segregated, and nutrients exported (e.g. in food) from rural/peri-urban areas are not being returned to support primary production in these environments. To redress these imbalances we propose the concept of the Peri-URban ecosystem (PURE). Through the merging of conceptual approaches that relate to Critical Zone science and the dynamics of successional climax PURE serves at the symbiotic interface between rural/natural and urban ecosystems and allow re-coupling of resource flows. PURE provides a framework for tackling the most pressing of societal challenges and supporting global sustainability goals.

Keywords: biogeochemical cycling, coupling, peri-urban ecosystem, urban-rural interface

Graphical Abstract



1. Introduction

Rapid urbanization, in many parts of the world, is driven by the desire for economic improvement coupled with the diminished employment opportunities in rural regions. As a consequence of unprecedented urbanization, globally more than 50% of the world population now live in cities (Grimm et al., 2008). The trade-off of urbanization is that less people now produce our food with an associated intensification of production, and agricultural land around metropolitan boundaries is being sealed over for buildings and transport infrastructure. Now, more than ever, the understanding and management of urban ecosystems have become an essential component of sustainable development.

A key feature of urban ecosystems is that nutrient stocks, carbon (C), nitrogen (N) and phosphorus (P), are being imported into urban ecosystem (through both natural and anthropogenic pathways). Significantly, these nutrients are not being returned to support primary production in rural/peri-urban environments from where they originated. For example, the food production required to sustain a city's population typically takes place in rural environments, but nutrient-rich wastes (resulting from food consumption) are emitted and processed in urban settings. Thus, reuse of urban nutrient wastes in rural and peri-urban environments is precluded from sustaining further production because: these wastes, and their associated nutrients, are often lost due to their discharge to water courses or incorporation in landfills; inadequate sewage collecting infrastructure and wastewater treatment approaches (that might realize suitable products to support soil improvement), and; a lack of mechanisms to return nutrients recovered from the urban environment to their point of origin. Overall, this cycle perpetuates a net gain of nutrients in the urban environment and a commensurate loss of nutrients from rural/peri-urban environments.

In order to redress nutrient losses in rural/peri-urban environments, and to sustain food-supply, chemical fertilizers are required to replenish this nutrient deficit. While this ‘fixes’ the soil nutrient problem the current use patterns of chemical fertilizers are unsustainable. Firstly, these practices result in the increased likelihood of nutrients being leached form soil into watercourses and causing damage to aquatic environments and additionally contributing to the rural to urban efflux of nutrients. Secondly, fertilizer production is heavily reliant upon with fossil fuels and as consequence production of inorganic fertilizers has a large carbon-footprint.

2. The concept of Peri-URban ecosystems (PURE)

If we are to realize global sustainability goals (inter alia: sustainable cities and communities; responsible consumption and production; good health and well-being; clean water and sanitation, and to protect and conserve life on land and below water) (UN, 2012) then the inherent conflicts between urbanization, food security and environmental sustainability have to be resolved in the longer term. One of the focal points related to rapid urbanization will be a sustainable food system for city dwellers. We propose that the concept of the holistic and self-sustaining Peri-URban Ecosystems

(PURE) is the key to ensuring food production under rapid urbanization. PURE is the symbiotic interface between urban and rural ecosystems, which should be designed and developed to produce food by assimilating domestic waste streams rich in N, P and energy, as well as more efficiently using a plentiful supply of treated domestic waste water that might otherwise be transferred to water bodies and exported out of the urban zone.

3. Defining the common framework of PURE

Defining and sustaining the PURE for urban-rural symbiosis requires outlining a common, integrating framework of quantitative analysis that encompasses the considerable structural and functional differences encountered across the rural-urban transition zone. We propose to define integrating systems concepts for the reconnecting of rural and urban environments, through PURE management. One contributing framework is the concept of Earth's Critical Zone as a vertically integrated system that links terrestrial and freshwater environments (Brantley et al., 2007; Richter and Billings, 2015). Earth's Critical Zone is the life-sustaining surface of the planet, extending from the top of bedrock through the land surface and vegetation to the atmospheric boundary layer (Figure 1). Critical Zone science, in particular, addresses the steep gradients in environmental conditions and the enormous variation in processes and their rates, from the outer lithosphere to the atmosphere, that exist along this vertical transect; often only 1-10 meters in length. This framework can be integrated with systems concepts of urban metabolism; i.e. the flows of energy and material that sustain the natural processes and human activities in cities. Thus, PURE needs to define the interfaces within the Critical Zone and how to accommodate the flows arising from urban metabolisms. In addition, PURE should establish boundaries within the urban ecosystem that define: stability, resilience and limits for resource and energy recovery.

What is missing so far is the quantitative understanding of the mechanistic linkages that couple the resource flows of the Critical Zone and the urban industrial economy and their resulting dynamic response to environmental and social drivers of the change across the rural-urban interface.

The starting point for an analysis framework that bridges the rural-urban transition zone is to define the connected flows and transformations of resources - mass, energy and genetic information (e.g. the microbiome and functional genes contained) - that embed the urban/industrial metabolism within Earth’s Critical Zone, the natural habitat of the urban consumer. The necessary quantitative analysis requires the concept of flows and transformations that occur from naturally-occurring processes in both rural and urban environments as the foundation for a sustained flow of environmental goods and services; for example, providing water and food, regulating climate, storing and transforming nutrients and supporting genetic biodiversity. These service flows interact directly with the industrial metabolism of material, energy and genetic flows that occur through industrial production, distribution and consumption – in effect linking the Critical Zone resource flows and transformations with industrial metabolism flows and processing. This merging of conceptual approaches directly addresses a major challenge which is the steep environmental gradients of change; vertically through the

Critical Zone, and geospatially across the rural-urban transition zone.

Applying these concepts to sustaining global food supply, requires the nutrient input, N and P in particular, to soils to offset continuous losses from land by crop uptake and harvest. "Nutrient urbanization" (enrichment of nutrients in the urban environment) will ultimately deplete global soil fertility and at the same time risk polluting the environment through urban waste discharges. The circular economy is often invoked as a concept to link urban nutrients (C, N and P) and other waste streams back to points within the ecological production system or its downstream points in the food supply chain; in this way re-coupling spatially separated nutrient flows and reducing impacts on the environment.

While such a circular economy philosophy might prove virtuous for the recovery and recycling of nutrients within the urban Critical Zone, the presence of chemical and biological hazards entrained within waste streams present a problem. In this regard pollutants from industrial discharges and originating within transport systems (that are transferred through surface water run-off corridors), and from domestic cleaning products and pharmaceuticals represent an impediment to the repurposing of urban waste streams. A second significant hazard present in urban waste streams is antibiotics and microbes carrying antimicrobial resistance (AMR) (Su et al., 2015).

How to re-engineer waste streams to separate out industrial and domestic pollutants in order to produce safe water and organic fertilizers for agricultural use is a major challenge for present and future cities.

4. The dynamics of PURE

To understand the dynamics of PURE, the transitions and the services that humans require in an urban setting needs to be understood. In this regard, the seminal manuscript of Clements (1939) provides a suitable scaffold to draw analogy between climax states in the natural world (in Clements' case the vegetation of North America) and climax states associated with urbanization (Clements, 1939). With regards to the latter the inherent managed development of urbanization within the rural-urban fringe, will achieve a stable disclimax state that is maintained by continuous human intervention; therein benefits to the human will be derived from sustaining desirable environmental services. The concept of spatially varying climax states, edaphic climax, gains new significance for PURE because of the potential to engineer intervention within the Critical Zone, for example, through water management interventions (drainage, irrigation, sealing), and removal or addition of specific soil types to modify Critical Zone topography, landscape, vegetation and the provision of entrained ecosystem services.

However, maintaining an artificial anthropic disclimax state comes with the risk of tipping points being reached. Such destabilization could result from displacement of urban ecosystem outputs to the periphery of the urban zone where they lead to damage to environmental services located much further afield to the original source of the discharge. As increasing amounts of waste are exported away from the urban zone these problems will be exacerbated. The Mississippi River delta represents a case in point. Here the export of nutrient wastes into water courses has led to off-shore eutrophication and “dead-zones” that have decimated fisheries (Rabalais et al., 2002).

Below, we conceptualize a trajectory of transitional states that an accelerated urbanization might assume (Figure 2). Akin to ecological succession, this urbanization succession captures (in the simples of terms) how an urban system might respond and adapt to the pressures of the particular transitional state; and, how this adaptation might then lead to the next state in the succession.

Recognizing the imbalance of flows (for example, nutrients, waste and pollutants), this conceptualization highlights key risks. Frame 2, represents the risk of the system becoming overburdened and resulting in transition from a status of sufficient delivery of environmental services to one of impaired services. Thereafter, continued urban growth successively increases the loci of the impaired zone (Frames 3 and 4). Eventually (Frame 5), intervention is made to abate the issues in one zone but to the detriment of another (i.e. displacing, not solving the problem). The short term intervention is transient and the loci of irreversible damage may reach a final tipping point where the urban center is subjected to intolerable pressure (Frame 6) and might ultimately collapses (Frame 7).

Thus, society needs to understand urbanization trajectories and how PURE can be applied to sustain urban Critical Zone services, to stabilize disclimax states, to mitigate risks and to avoid final tipping points being reached.

5. Managing PURE

Two aspects are of particular relevance to the management of PURE. Firstly, the intrinsic limitations of the waste flows themselves, and, secondly, the prevailing condition of the environment to which these flows are to be redirected. For example, in

Beijing, 5374 t and 849 t of P in total were, respectively, consumed by urban and rural residents, in 2008 (Qiao et al., 2011). The largest outflow of P through food consumption in the city is discharge to waste water treatment plants (WWTPs), representing about 3861 t P; of which: 394 t P was discharged, after treatment, into natural aquatic systems; 544 t P was recycled through reclaimed water, and; the remaining 2923 t P was transported to landfill sites in the form of sewage sludge. In an analysis on nationwide P metabolism in cities (Li et al., 2012), it was estimated that on average 19% of dietary P inflow to cities remained within the urban environment leading to the buildup of excessive P that has the potential to cause damage to urban and peri-urban aquatic ecosystems.

While urban environments are rich in excess heat energy, water and N and P, these resources are invariably of lower value to industry than those of primary inputs i.e. heat density in waste flows may be far less than from primary sources and nutrient waste flows can often contain chemical pollutants. As a consequence repurposing these flows can attract additional monetary and environmental costs (e.g. associated with their reprocessing and separation) and this further detracts from their ‘value’ when compared to primary inputs.

It is well recognized that urban areas tend to have higher air temperatures than surrounding rural areas (Akbari, 2005). This is underpinned by the engineered modifications that have replaced natural vegetation with buildings and roads within the urban environment. Cities, having been altered in this regard, do not receive the natural cooling benefits of vegetation and, as a consequence, air temperatures rise. This has the knock-on effect of increasing the demand for air-conditioning and, this then leads to higher emissions from power plants. Together these increased emission and higher air temperatures, intensify smog formation (through photochemical reactions that are promoted at higher temperatures). Akbari (2005), reported (for the USA) that increased urban air temperature were responsible for 5–10% of urban peak electric demand (to support air conditioning), and as much as 20% of population weighted smog concentrations in urban areas.

In abatement, PURE would seek opportunities to vegetate the urban environment, for example, the creation of "sky roof gardens". This intervention vegetates the roof of buildings and thereby reduces solar radiation from reaching the building structure, reduces temperature indoors and thereby decrease demand for air conditioning. In addition, the establishment of roof vegetation brings the potential for collateral benefits: i) reduce the need for winter heating, ii) reduced storm water run-off, and, iii) carbon sequestration (Pandey et al., 2012).

Dependent on past land-use, soils of cities are characterized by having elevated contaminants compared to agricultural land situated far from urban centers. Household detergents, pharmaceuticals, metal(loid)s and persistent organic pollutants (POPs) characterize urban water and solid waste streams. Thus, peri-urban agronomic systems must be designed to use contaminated waste streams without potential negative impacts on land and water, or on consumers of arable produce originating from land to which these waste streams are applied.

With these factors in mind, we recommend that both the flows being repurposed and the agronomic land in and around cities should be graded as to their suitability with respect to food safety. Such an approach poses two challenges:

Nutrient waste streams such as wastewater sludge must be graded for contaminant content and risk, with separation of unsuitable waste streams for more intense processing to remove or stabilize chemical/microbiological hazards before further use. Clean waste streams would be processes into forms suitable for organic fertiliser and agronomic use.

Land must be graded according to pre-existing contamination levels in the soil. Wastes of acceptable hazard could be used for non-edible crops while only non-hazardous wastes could be used to support edible crop production (Zhao et al., 2014). Thus, the most contaminated zones could be used to produce building materials such as bamboo, zones of intermediate contamination for textiles and biomass crops, with graduation to a rural baseline that is deemed suitable for food production.

Conflating these elements, a PURE-zonation would emerge based on the historic contamination status of the soils and the ‘grade’ of waste that could be applied within a particular zone. Herein, however, lies a conundrum, as the most contaminated land will usually be near urban zones, and waste streams that are tainted with chemicals or microbes are to be applied to contaminated land this will exacerbate damage to the Critical Zone services at locations that are closest to the highest population. A further consideration is that working relatively contaminated land (e.g. cultivation that disturbs the soil) will produce dust, and dispersion of this dust could lead to unacceptable risks to health. In this scenario, a tipping point, beyond which irrevocable damage to PURE or human health, could be reached.

Conflating issues that relate to repurposing sewage sludge, improving soils for agriculture and abating pollution issues associated with urban soils PURE draws upon recent advances in the pyrolysis of sewage sludge. Here sewage sludge is used as a feedstock in the production of heat and power using pyrolysis. This delivers an immediate benefit of waste diversion to sustain heat and power demands. Pyrolysis of sewage sludge (and indeed other organic materials) generates biochar as a co-product. This carbonaceous material is potentially a long term store for carbon and, because the carbon it entrains originated in the atmosphere (before being fixed though photosynthesis into to biomass e.g. crops) biochar burial represents an opportunity to abate the anthropogenic elevation of atmospheric carbon dioxide. Biochar has been widely reported to improve soil productivity (Jeffery et al., 2011). Furthermore, biochar has also been successfully applied to reduce soil to crop transfer of pollutants and thereby improve food safety and security (Khan et al., 2014). This synergy of waste diversion, heat and power generation, soil improvement and pollution abatement exemplifies the PURE concept.

Finally, wastewater from urban sewage and manures pose a risk, as their application to land introduces pharmaceutical compounds directly into the human food chain. Furthermore, recent reports have highlighted the occurrence of antibiotic compounds in peri-urban agronomic soils receiving organic waste streams, with additional evidence indicating the presence of AMR genes both in the receiving soil/water (Wang et al., 2014; Chen et al., 2016) and in the tissue of plants grown in these environments (Hough et al., 2004; Kohrmann and Chamberlain, 2014). Thus, an emerging risk from aggressively closing nutrient cycles for PURE symbiosis is the potential for trophic concentration of AMR and health risks to the top consumer – the urban human. It is important to acknowledge that pathogens exhibiting antibiotic resistance can spread globally through air and water circulation, export of agricultural products and associated with infected travelers. Thus, while AMR issues might appear, on first glance, to be endemic to a defined urban zone they are, potentially, of pandemic significance.

To address this risk, new research is needed to: quantify the occurrence of pharmaceutical compounds in waste streams and receiving agricultural environments; quantify the occurrence and rates of AMR development and transfer within the urban Critical Zone, and; to develop approaches to waste stream processing that capture nutrients while abating chemical and microbial risks, and; evaluate the efficacy of changes to farming practices that might adequately manage these chemical and microbial risks.

6. Concluding remarks

Globally, the urbanization pace is not going to slow down. In China, for example, an unprecedented migration of people from rural to urban environments has taken place over the last 20 years. The urbanization of China's population is set to continue, and indeed intensify, with 250 million rural people being projected to migrate to urban centers by 2025. When set alongside current populations of, for example, New York (8.5 million), London (8.5 million) and Tokyo (13 million) such a figure is immense. Urban populations in China reached the 50% landmark in 2010 (Chan, 2012). Given that 80-90% of the total national populations of the USA, the UK and Japan reside in urban centers; it is staggering to acknowledge that around 400 million people would need to migrate from rural to urban locations if China were to attain a comparable proportion of its population residing in urban centers.

Cities have idiosyncratic histories based on past and current economies, and when they rapidly expanded or collapsed. At one extreme, there is the rapid expansion of new Chinese mega cities, e.g. of the Yangtze Delta, built on agricultural land with little or no pollution histories; with this also being the case in many agricultural regions worldwide where urbanization proceeds through land take within highly productive agricultural regions. This situation contrasts with the decline of industrial cities, for example in former regions of heavy manufacturing in North America and Europe where population densities in their industrial heart have declined and in some cases collapsed leaving large zones with contaminated soils and with a remaining large suburban population on relatively uncontaminated land (Brown and Jameton, 2000; Zezza and Tasciotti, 2010). It is clear that cities need to be considered on a case by case basis with respect to how to re-engineer them for the most sustainable recycling of waste streams to optimize peri-urban agriculture and other ecosystem services (see our conceptual model illustrated in Figure 3).

To solve the problems associated with urbanization, we cannot simply expect people to go back to rural society, but require a step change in managing urban-rural biogeochemical cycling and ecosystem management. The PURE concept will offer the opportunity of developing cities in a more sustainable way. While it is difficult to practically adopt the PURE concept in retrofitting an already designed city, PURE concept can be implemented in expanding cities and/or emerging cities. It is predicted that in the foreseeable future, urbanization will happen mostly in many under-developed countries, where investment in infrastructure is constrained, therefore managing PURE is a more pressing and urgent need in rapidly urbanizing countries. Although deferent pathways maybe taken in integrating PURE concept in managing cities in developed v.s. developing world. The goal of implementing PURE concept in urban management is to maximize ecosystem services for urban health and wellbeing. Indeed, securing ecosystem services for urban population is indispensable in implementing sustainable development goals (UN, 2012), as world is increasingly becoming urbanized.

Acknowledgments

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Figure 1 The vertical architecture of the Critical Zone (a) and the geospatial gradient in land cover and density of human infrastructure across the rural-urban transition zone (b).

Figure 1

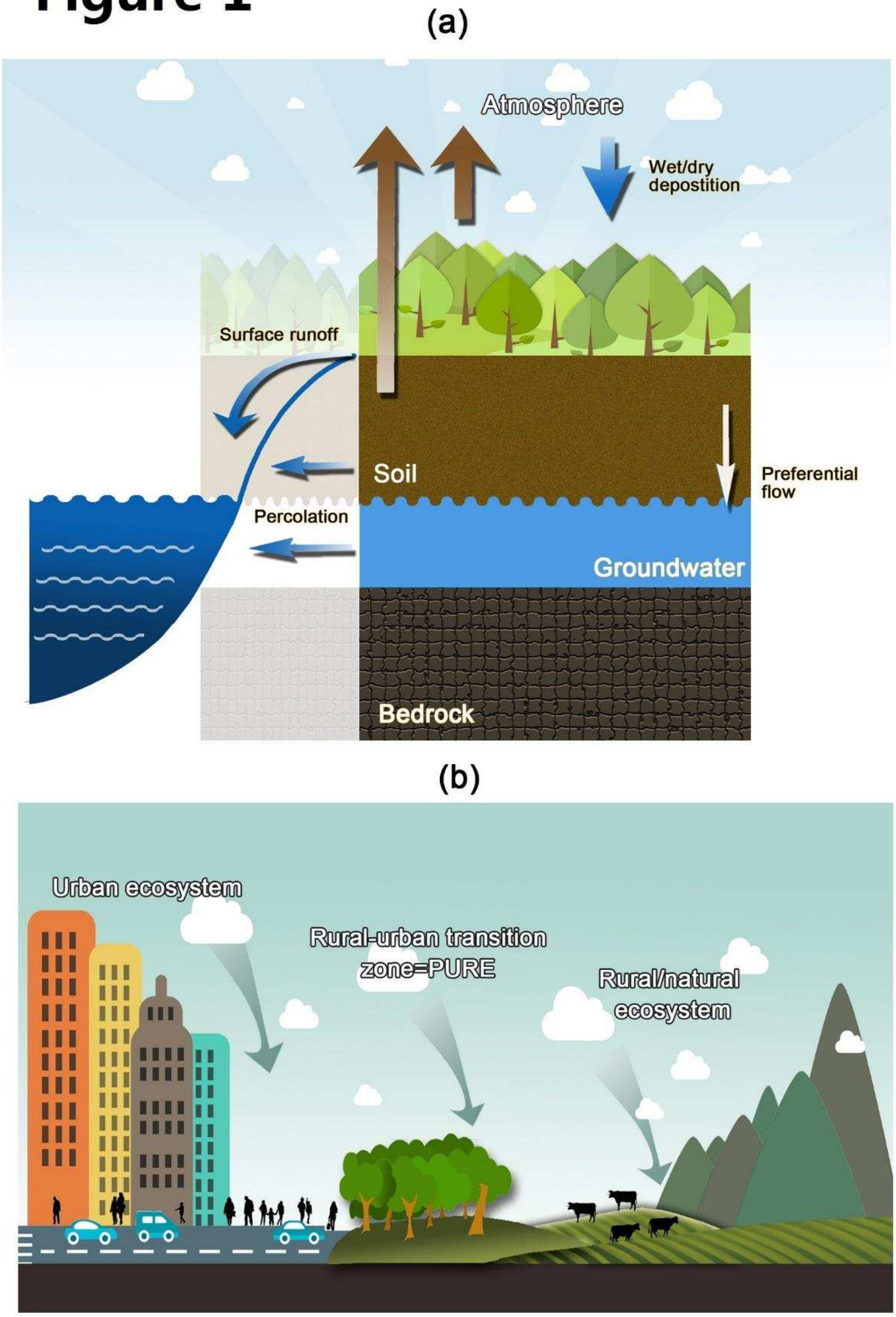

Figure 2 A trajectory of transitional states of an accelerated urbanization

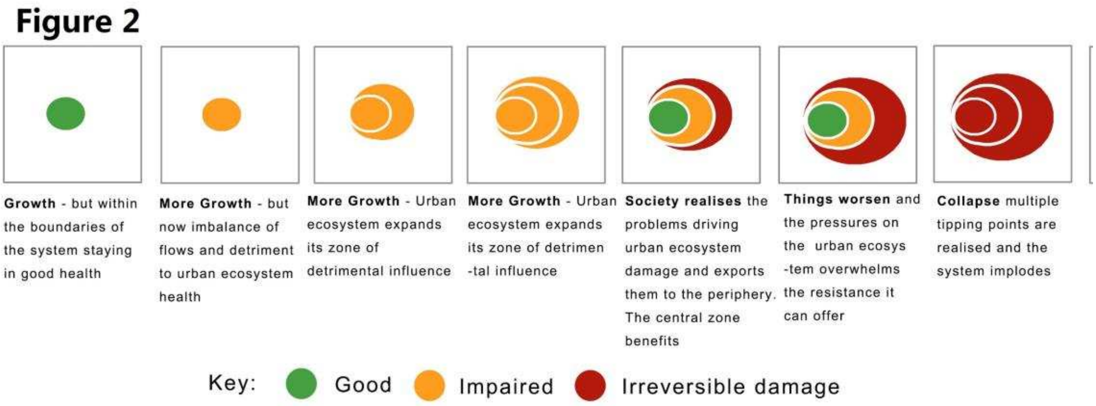

Figure 3 A conceptual framework to integrate the interactions between urban and rural/natural ecosystems using Critical Zone Science.