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# Understanding rural-urban transitions in the Global South through Peri-Urban Turbulence

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## Abstract

Much previous research has problematised the use of a binary urban-rural distinction to describe human settlement patterns in and around cities. This paper presents a framework that conceptualises rural-urban transition through the prism of shifts in natural, engineered and institutional infrastructure, in order to explain the processes of rapid change and the dip in service provision often found in peri-urban areas in the Global South. We draw on examples related to the provision of water and sanitation to illustrate the theory and discuss its implications for future research on the peri-urban.

**Key Words:** Infrastructure, Peri-urban, Rural, Services, Urban expansion, Urbanisation

## Introduction

For much of this century, the world's urban population will continue to grow leading to an increasingly urbanised planet[1]. A significant consequence of this demographic change is urban expansion, as cities extend outwards incorporating land around them. This expansion of cities is evidenced in high income countries[1,2], where urban population growth is modest, but the trend in developing countries in Asia and Africa is especially rapid[1,3]. This creates ever larger areas of interface between the urban and rural. Depending on the definition, approximately 1 billion people were living in peri-urban areas in 2015, with the proportion of peri-urban inhabitants particularly high in low- and middle- income countries[4]. The magnitude of population living in these areas challenges the usefulness of a dichotomous categorisation of urban and rural areas and reaffirms the importance of further theoretical and conceptual development of the peri urban interface[5–7].

Peri-urban areas are, by nature, complex, multifaceted regions, and so the literature on these areas is spread across numerous disciplines. For example, there is significant scholarship on environmental and ecological conditions[8] as well as literature on changing patterns of land use[9]. Research has been emerging on 'cityness'[10], 'urban' activities in rural spaces, such as wage employment[11], 'rural' activities such as agriculture in urban spaces[12], middle-class colonisation of rural areas[13], understanding the interdependence between these two realms[7] and finally the livelihoods and resource management issues at the interface between the urban and the rural[3,14].

There is therefore a need to bring these disparate themes together in an examination of the peri-urban, what Allen describes as:

> *"a lumpy rural–urban continuum that challenges conventional distinctions between the urban and the rural … where cities' appropriation and transformation of nature's nutrient cycle manifests most intensely."*[3]

Allen[3] goes on to argue that peri-urbanisation is a process that sees tensions between the imperatives of economic growth and natural productivity. The result is a zone of intensely heterogeneous activities in space, time and nature that frequently include subsistence and peasant farmers, abattoirs, squatter settlements, reservoirs, factories and mining activities side-by-side. This raises significant questions about the provision of infrastructure and services, about the ability of peri-urban interfaces to provide "*inclusive, safe, resilient and sustainable*" settlement as envisioned in the Sustainable Development Goal 11 on sustainable human settlements[1].

Box 1 – Key definitions for a theory of Peri Urban Turbulence in cities of the Global South, drawing on environmental and urban studies literatures.

- Urban: the territorial area of a city typically characterised by high population density, a significant built infrastructure endowment and municipal governance mechanisms.
- Peri-urban: the territorial area on the edge of an urban settlement typically characterised by rapid growth in population, mixed land use between agriculture, industry and housing and fragmented governance systems. Some densely populated rural areas may display similar characteristics.
- Rural: the territorial area beyond peri urban and urban areas, typically characterised by lower population density, significant agricultural land use and greater prominence of community-based institutions.
- Natural infrastructure: defined as ecosystem services, which are the benefits humans derive from nature (also known as nature's contributions to people).
- Engineered infrastructure: the endowment of built structures and facilities that enable the provision of infrastructural services, such as water and electricity.
- Proximate institutional infrastructure: the formal and informal institutions that are concentrated within communities, such as community groups or local service providers, which manage public goods and deliver services.
- Distant institutional infrastructure: the formal and informal institutions that are dispersed across communities, such as municipal councils and public utilities, which manage public goods and deliver services.

Previous conceptualisations of the challenge of sustainable human settlement involve comparisons and contrasts between urban and rural which leads to a partial understanding of lack of services. There are approaches that theorise the urban and rural as areas that are in competition over resources and services [15]. For example, Lynch[5] highlights the relationship between the city and countryside that can be generic – complementary trade in agricultural goods and natural resources such as food, fuelwood and water – in exchange for finance, manufactured goods and services. However, this relationship can also be exploitative, drawing more value from the rural to the city, with limited return trade. A number of studies that indicate that urban demand places pressure on rural woodfuel sources, but that the research suggests that the pressure is mediated by 'institutional scarcity'[16,17]. There are also examples of competing economic values applied to peri-urban land – direct use value, indirect use value and non-use value – or the benefits from not using natural resources, such as protection of wildlife, green space for leisure or wildlife conservation[18]. In this paper, we focus on the transformations that occur at the frontier of urbanisation and examine how the systems that underpin basic service provision, such as water and sanitation, and enable the management of public goods, like the land or green space, shift during rural-urban transition. We combine literature and theories from urban studies and ecology to form a new framework that explains a peri-urban dip in service provision and process of rapid change we characterise as 'peri-urban turbulence' (PUT).

The theory of PUT presented in this paper is based on the concept of shifts in the balance and magnitude of natural and engineered infrastructure and local and distant institutional systems during transition primarily in fast growing urban areas of the Global South (Box 1). We characterise natural infrastructure through the prism of ecosystem services – the benefits people derive from nature – especially those associated with regulating services whereby we recognise the role of the environment in purifying water and processing wastes. Engineered infrastructure includes the endowment of built structures and facilities that enable the provision of services, such as reservoirs, pumps, treatment plants and piped distribution networks that can form a water distribution system. The distinction between proximate and distant institutional infrastructure reflects partly the relative scale of institutional systems that underpin basic service provision. Here, we account for the unit of service management between local models of household (self-supply) and community-scale provision against more distant forms of municipal or large-scale market provision. However, it also reflects a distinction between the prominence of more localised institutions in broader areas of rural life, such as community groups, and the more dispersed, impersonal institutional systems that fulfil similar roles in urban life, such as municipal councils. We believe conceptualising the shifts in the balance of natural, engineered and institutional infrastructure can help explain the varied mechanisms through which citizens meet their needs and communities manage public goods across rural, peri-urban and urban areas.

Building on this introduction to the constituent parts of the PUT theory, the next section reviews literature on the peri-urban condition and assesses evidence on the reported distribution of engineered, natural and institutional infrastructure across urban, peri-urban and rural areas. It draws on examples from the water and sanitation sector to illustrate similarities and differences across these zones. The PUT theory is then unpacked and explained in more detail before a discussion about its implications on future research on the peri-urban and concluding remarks are provided.

**The peri-urban condition**

The expansion of peri-urban areas and the growing evidence of their relative neglect highlight their importance in addressing global poverty, however what we know about these areas is obscured by demographic statistics that distinguish between urban and rural populations, thus splitting the peri-urban between these categories[19]. Recent work has sought to better characterise the peri-urban condition. One study into child health in East Africa found that it was lowest in the peri-urban interface between the city and rural areas[20], whilst a study in South Africa found that around two thirds of urban and rural citizens report that their quality of life had improved over the last five years, but only half of respondents reported such improvement in peri-urban zones[21]. The literature is clear that peri-urban environments can amplify health inequalities[22–24]. Rapid urbanisation can overwhelm local water supply and sanitation systems and coupled with high-levels of animal ownership this leads to higher infectious disease burdens[22]. Weiss and McMicheal[22] argue that these peri-urban dynamics are contributing to a *"major transition in the human-microbe relationship"* that is contributing to an unprecedented era in terms of the emergence and spread of pathogens, from the re-emergence of cholera to new infectious diseases such as SARS (and now COVID-19). In this view, the transitional status of some peri-urban areas represents not only localised welfare issues but also global health security risks. This is further compounded as peri-urban populations are also likely to be exposed to 'urban' co-morbidities linked to issues such as air pollution or lower levels of physical activity[23].

Assessing the endowment of engineered infrastructure in peri-urban areas is complicated by the structure of most global datasets not using this classification. Those datasets clearly show that urban populations are more likely to have access to infrastructural services, such as water supply and electricity, than rural populations[25,26]. It is hypothesised that peri-urban areas are likely to sit between the urban and rural levels. However, in interpreting this distribution of infrastructure, it is important to recognise that the welfare costs associated with a lack of access are likely to be higher in peri-urban areas than rural areas. This is because in rural areas ecosystems can fill gaps in infrastructure service provision[27] or reduce the risks associated with low levels of infrastructure by absorbing wastes that leak into the environment before they impact human health[28]. Based on this logic, we would hypothesise that peri-urban populations are often faced with middling access to engineered infrastructure but the highest exposure to risks associated with inadequate access.

Similarly, the flow of ecosystem services to inhabitants within peri-urban areas is poorly understood. Provisioning services (e.g. fuel, food, and water; provisioning services) might be most accessible nearby the ecosystems that produce them and in areas where they can be transported easily (e.g. via value chains[29]), potentially resulting in a dearth in peri-urban areas where local ecosystems are degraded but transport networks are not fully established. Regulating services (e.g. maintaining the quality of air and soil, providing flood control; regulating services), by their very nature, are often not transportable as they prevent, moderate or structure natural processes. As such, regulating services might be best noticed by their absence. In rural areas, healthy ecosystems help maintain habitable environments, but increased pressure from higher population densities can disrupt these processes leading to increased flooding, droughts, soil erosion and disease[30]. Where established, engineered and institutional infrastructure can mitigate some of the disruption resulting from a loss of regulating services (e.g. paving slopes where vegetation has been lost reduces the probability of landsides). Furthermore, people living in rural areas may have more direct access to cultural ecosystem services (e.g. the ability to develop our mental, physical and spiritual wellbeing; providing space for recreation, spiritual and aesthetic appreciation of nature) than those who live in urban areas as they are often physically closer[31], although good city planning can preserve access to these services by maintaining urban green space, as well as providing good transport links to natural areas[32].

Focusing on the differences and similarities in the institutions that underpin the delivery of services and the management of public goods, it is common that the urban and rural categorisation is used as an organising logic for distinguishing between different institutional environments. For example, across much of South Asia, the Panchayat Raj (village council) system of local government reflects a form of direct local government that has historical roots back to precolonial periods[33]. In rural areas, large-scale infrastructure development will be overseen by state-level agencies, but many households and communities will manage basic services, such as water supply and sanitation, themselves or via community-based management mechanisms. In this context, service provision is best described as being coproduced between household, community and government[34]. We conceptualise such arrangements in this paper as proximate institutions, which we formally define as the formal and informal institutions that are concentrated within communities, such as community groups or local service providers, which manage public goods and deliver services in those areas.

This compares to urban institutional environments whereby entities such as a municipal corporation take direct control or supervise specialist city-wide institutions such as metropolitan water boards to develop and run infrastructure to deliver services. In such cases, citizens and communities have a much more passive and distant role. These formal urban service delivery systems often exclude many citizens and therefore an ecology of formal and informal private sector providers, such as water tankers and vendors[35], also play a role. However, the ultimate 'fallback' option of self-supply is greatly diminished compared to rural areas. In this paper, we conceptualise this environment as reflecting distant institutions, which we define as the formal and informal institutions that are dispersed across neighbourhoods, such as municipal councils and public utilities, which manage public goods and deliver services.

In peri-urban areas there is even greater heterogeneity as the rural based models become degraded by growing and dynamic populations, eroding the potential for community-based models, and reducing space for self-supply, yet the urban service delivery models are yet to mature[36,37]. This process creates a series of poorly recognised institutional tensions in peri-urban regions. For example, in many neighbourhoods long established households will rely on pre-existing infrastructure, either at the household or community level, and can be resistant to shift to new management paradigms that may require paying for services at higher levels than before[37]. Similarly, there are often governance tensions as rural authorities are hesitant to accept processes of municipalisation that will see local political leaders power subsumed into larger governance units[38]. In parallel, municipal authorities may often be hesitant to expand their authority to include peri-urban areas whereby the management of public services and goods is challenging[38]. These institutional dynamics mirror the infrastructure and ecological transition that unfolds within the peri-urban sphere.

In summary, the peri-urban is a transitional site whereby the relative capacity of natural infrastructure to support populations is reduced compared to rural areas, yet the endowment of engineered infrastructure is not yet materialised. Communities are often mixed with some residents well embedded in proximate institutional networks, yet community-based management approaches and other similar proximate models become stressed by much higher populations. The expansion of more distant institutional systems, such as those characterised by municipal governance, often lags behind the change in settlement character towards urban-like conditions and can be fragmented across peri-urban regions resulting in a patchwork of institutional forms[3].

**The Peri-urban Turbulence framework**

To help explain why these processes unfold as they do, we propose a theoretical model for rural-urban transitions that argues that changes in natural, engineered infrastructure and distant and proximate institutions represent important markers of rural to urban transition, especially in the Global South. The high-level logic of the PUT framework is derived from four (or more) semi-independent transitions: 1) high levels of natural infrastructure (e.g. ecosystem services) are associated with rural contexts with these being low in urban areas, whilst 2) engineered infrastructure follows the reverse pattern. Similarly, 3) an inverse relationship exists between proximate institutions (high in rural areas and low in urban areas) and 4) distant institutions. In this view, as cities grow nearby settlements experience deep-rooted transitions as their character shifts from 'rural' to 'urban', but this includes an intermediate period of poorly delineated and defined peri-urban existence that can last decades, whilst being characterised by rapid spatial and temporal change and uncertainty. The peri-urban character reflects the instability between the two systems whereby there is higher flux in land use, livelihoods, resource use and services; a transition which we label as PUT (Figure 1), with 'peri-urban turbulence' suggesting a lower level of natural, engineered, proximate institutional and distant institutional infrastructure in peri-urban areas.

Figure 1 here

**Figure** 1 - Levels of infrastructure vary across rural, peri-urban and urban areas. Access to services varies across individuals within each area (arrows) and nature may act as a safety-net in many areas across the Global South (dashed green line).

Developing this theory, we draw analogies with but key differences to the red-loop and green-loop theory of rural and urban systems[39,40]. Red-loop and green-loop theory describes how local natural infrastructure declines during urbanisation, but how engineered, social and institutional infrastructure may fill this gap. In a green-loop system, the overarching pattern is one of direct use of local natural resources[40]. By contrast, in urban areas there is an increased reliance on socioeconomic infrastructure across larger spatial scales (e.g. regional)[40]. A wide variety of evidence supports this theory across a range of ecosystem services, from food production (e.g. subsistence agriculture in rural areas vs transport chains for urban supply[41]) to fuel use[29]. However, there are notable exceptions – e.g. in both rural and urban areas, proximity and access are factors in how much time people spend in green space. Living nearby an urban green space does not necessarily mean people spent time there[42], as there is a need for some level of connection to nature for people to want to spend time there and gain the associated benefits[43].

Figure 2 here

**Figure** 2 Conceptual model of the relationship between the processes of urbanisation and ruralisation.

The 'peri-urban' character reflects the instability between the two systems whereby there is higher flux in land use, livelihoods, resource use and services. This transition, which we refer to as 'peri-urban turbulence', resembles a hysteresis loop and can move in either direction, but with a 'service gap' in the peri-urban space between rural and urban dynamic equilibrium states (illustrated in Figure 2). Historically, urbanisation is the dominant trend, but examples of ruralisation also exist[44]. Although for the purpose of PUT we emphasis instability of the peri-urban, we recognise that some may conceptualise rural, peri-urban and urban areas as three related complex adaptive systems that each cycle between phases of stability and change, within the larger system of how humans organise our biosphere.[5, 6]

When establishing red-loop/green-loop theory, Cumming et al[40] suggest a transitional state whereby both local natural infrastructure and distant socioeconomic infrastructure are benefited from simultaneously but distant services predominate as urbanisation progresses. We suggest that this transition is not always perfect, leading to a hiatus between services. As a result, peri-urban areas may not experience the best of both worlds (as might be inferred from red-loop/green-loop theory) but instead go through a temporary void until infrastructure is able to provide access to distant services. In other words, PUT likely results in both reduced local ecosystem services and a dearth of engineered infrastructure that might enable these benefits to be supplemented from distant natural infrastructure. These 'gaps' are of high social and political importance when the loss of services results in a large reduction in wellbeing (e.g. sanitation services).

We hypothesise that both the rate of ecosystem degradation and the cost of establishing engineered infrastructure are major drivers in determining the dearth of services in peri-urban areas. For example, when the cost of supplying the service is high for the environment, then nature can only support low population densities. Similarly, when the cost of building infrastructure is also high, then it is only economically viable at high population densities. In a situation such as this, the green-loop system is likely to degrade prior to the red-loop system being fully established. For example, in low population densities pit latrines can be used safely, relying on natural processes within the soil to make the waste safe[28]. However, since establishing sewerage and sewage treatment plants is expensive, it is only viable to develop this infrastructure when economics of scale enable. Thus, medium population densities in peri-urban areas are likely to experience unsafe sanitation – where nature's services are overwhelmed but engineered alternatives are not yet established. The likelihood of such a gap in infrastructure is increased as the institutional environment is also in a state of flux and therefore is unable to create viable solutions.

This type of negative spiral in peri-urban areas is greater for some services than others, and varies across geographic areas. For example, food production predominantly occurs in rural locations, but can continue within urban areas[45]. Even without urban agriculture, food can be transported within cities with relative ease via transport infrastructure[46] (which are relatively cheap when compared to other forms of engineered infrastructure [e.g. sewerage]). Similarly, an imperfect transition between natural and engineered infrastructure can be avoided through good governance and strong land tenure. For example, some natural infrastructure can be conserved throughout urbanisation through good city planning enforcing protection of green space despite heightened pressure for building developments. As well as this, large scale distant institutions, such as municipal water utilities, can subsidise the provision of services to increase viability at lower population density (e.g. provision of water supply is cross-subsidised from metropolitan areas to small towns and neighbouring rural areas in Uganda[47]). As such, we anticipate PUT to be stronger in areas whereby these forms of cross-subsidies do not exist and the transition in peri-urban areas proceeds unsupported.

Although we hypothesise that peri-urban areas have the worst overall turbulence, there are likely to be significant differences between groups living in each context. For example, higher income households and communities living in peri-urban areas will cover the relatively high costs of developing engineered infrastructure and therefore overcome the dearth of services. This manifests most visibly in the phenomena of suburban gated-communities that are now common in major cities of Africa and South Asia[6]. High-income households can also invest in facilities, such as generators, private boreholes and septic tanks to overcome a lack of some services. Low income peri-urban residents will be less able to overcome this lack of engineered infrastructure whilst their options for using natural infrastructure systems is reduced or constrained, as compared to rural citizens. This magnifies inequality as a lack of local natural infrastructure (i.e. as red-loop systems develop[40]) decreases the resilience of households. Particularly, as more vulnerable households are often the most dependent on local natural infrastructure (either directly or indirectly[40]), both for their livelihoods[48] and as a coping strategy for buffering shocks[49]. Thus, the ability to rely on natural infrastructure as a safety net is reduced during urbanisation, potentially resulting in large reductions in wellbeing for those unable to access alternative services, or when these services fail as a result of a shock. For this reason, peri-urban areas face the starkest inequality with citizens that are not well served or integrated into the urban institutional systems or which have access to engineered infrastructure, facing limited alternative options. In this case, they are excluded from the institutional safety nets of the state and nature.

**Peri-urban Turbulence as a research agenda**

PUT points to the importance of improving our understanding of the peri-urban condition and dynamics. We believe what happens in these settings will determine global society's ability to meet many of the critical challenges of the next decades. As we have argued, under current paradigmatic approaches the necessary expansion of core services such as water and sanitation will be hardest in these regions and the populations living in such environments will be limited in their ability to overcome this gap in provision. This not only represents an issue of immediate human need, but creates a series of broader risks and opportunities. This includes environments in which it is more likely that emerging infectious disease can arise and spread[23] but these settings are also where people are re-setting a pattern of living that will determine their future ecological footprints. Here, we see significant opportunities in viewing the peri-urban as a site for creating more sustainable futures as well as a site for monitoring and responding to local and global risks. Red-loop and green-loop theory emphasised the danger of urban populations having consumption levels so high that they over-exploit distant ecosystems[40] and we should be wary of responding to PUT by simply accelerating the rate at which populations move towards these types of unsustainable consumption levels, thereby heightening global environmental risks. We believe research is required to understand whether the peri-urban is an opportunity to create more sustainable urban models that allow the meeting of human needs within acceptable ecological boundaries[50]. Some localised and sector-specific efforts on issues such as travel[51] and urban agriculture[45] may hold some promise yet there needs to be further examination of the peri-urban governance and service delivery challenge to accelerate and scale up such work.

We argue that PUT may occur through the interaction of numerous tipping points, resulting in a 'perfect storm' of poor infrastructure (e.g. natural, engineered, institutional etc.; Figure 1). The critical thresholds at which each system will tip (e.g. the population density at which household-based on-site sanitation is no longer safe and sewerage or supported faecal sludge management is required[28]) are notoriously hard to identify but more research can help unlock important insights on when such thresholds might be realised and the multiple pathways to avoid them. Here, we see value in bringing together conventional urban studies literatures[3,5] with contemporary work on studying systems change from rural perspectives[34,41,52] and other disciplines[53–56]. For example, this integration could inform urban and rural planners, designers and architects, to build into their practice wider systemic perspectives that take account of the peri-urban[57]. There is a need to develop pathways based on work such as this to address the services deficiencies in the peri-urban in ways that are sustainable in the long term.

The systems change literature provides conceptual frames and methods for studying early warning signals in system change, such as 'flickering' and 'critical slowing down' that have been used to predict when a system might collapse[53]. As such, taking the example of sanitation provision, as the critical threshold population density is approached, the on-site sanitation system of latrines might be safe for most of the year but 'flicker' to an unsafe state during points of stress such as high precipitation when flooding latrines may cause problems within densifying neighbourhoods. Similarly, the proximity to the tipping point is closer as the ability of the system to recover from these high rainfall periods slows down (i.e. from becoming safe a few days after heavy rainfall, to taking substantially longer). Such patterns have been identified in a wide range a systems, from shifts in freshwater lake systems[53] to critical transitions in financial markets[55].

Methodologically, these 'early warning signals' are difficult to identify in advance, often being observed only with hindsight – although cutting-edge methods are being developed to address this[54]. Here, we draw analogies between deforestation (reduction in forest areas) and urbanisation (expansion of urban areas). Studies comparatively investigating rural and urban areas are well suited to identify many of the impacts of urbanisation (akin to analyses comparing pristine forests with agricultural fields to understand the impacts of deforestation). However, in order to identify the proximate and underlying drivers of these processes, it is necessary to study the frontier[58]. Ecologists produce high-resolution annual maps of deforestation to track this frontier[59]. Such maps can be used to 1) identify the drivers behind the expansion of the frontier, including down to individual-level motivations[52] and 2) anticipate the future expansion of the frontier[60]. Applying similar methods to peri-urban areas could lead to a step-change in urbanisation research, e.g. with annual, high-resolution maps of frontiers of urbanisation highlighting key locations for in-depth investigation to follow the process as it occurs. Given the far-reaching consequences for sustainable development, enhancing our understanding of PUT is an important goal for future research.

**The way forward**

In proposing this framework of PUT as a route for new research, we are aware that any systems-level analysis of rural-urban transition is necessarily abstract and therefore does not account for the varied experiences of individuals living within such systems. There are many rural communities and households that will be 'rich' in infrastructure and linked into distant institutions, whilst urban ones that are comparatively poorer across these markers. However, we believe the meso-level of analysis which we adopt in the framework is still useful as it provides a way of conceptualising rural-urban change in a way that provides an explanatory account for often found deficiencies in peri-urban services and wellbeing. This is a generalisable challenge and this framework provides a robust foundation for building a research agenda that can help address it. We accept that this work is largely conceptual in nature and the next stage will be to validate the framework through comparative datasets and case studies of rural-urban change, but we note evidence presented from the literature throughout this paper that reflect the patterns of outcomes we have discussed and which we believe supports the central tenor of our argument. Moving forward, we believe it is imperative to focus on responding to PUT and to answer questions on when and how authorities can respond to rural-urban transition to ensure the services and public goods are best maintained in a socially and ecologically sustainable way. This may create tensions for urban administrators over their responsibility to provide services for the dwellers in these regions:  At what point should they extend their boundaries to incorporate new urban areas? At what point do city authorities include in-migrants? Responding to this dynamic process has implications for a city's ability to meet the needs of its residents and therefore its key performance indicators. Future research in this area should be directed towards supporting such policy challenges and developing pathways to address these concerns. This Perspective develops PUT as an analytical framework to reveal the deficiencies in services experienced by those living in the peri-urban and the implications for both the urban and the rural. There are multiple potential pathways shaped by the specifics of context, rate of change, institutional capacity at various scales and degree of disparity (or sharpness of the boundaries) between the rural and urban, amongst others. The numerous possible combinations of these few variables results in a large number of possible pathways.  We believe that system-based approaches for studying rural-urban transition can be used to better anticipate, predict, and explain systemic change thresholds and therefore the basis for pathways to better futures.

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P.H., S.W. and K.L. led the conceptualisation and writing of the paper. All authors contributed to conceptualization and editing. All authors have read and agreed to the published version of the manuscript.

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**Competing interests**

The authors declare no competing interests.