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Mitigating Urban Fragmentation: A Comparative Assessment Of Green Bridging For Peri-Urban Landscape Resilience

Ar. Rashid Ali Khan	Assistant Professor, Dept. of Architecture, School of Architecture & Planning, UMT, Lahore
Sehar Dogar	Interior designer, fine artist & Assistant professor COMSATS, Lahore.
Ar. Naveed ur Rehman Anwar	Assistant Professor, Department of Architecture, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta.
Ar. Alishpa Naveed	Practicing Architect & Interior Designer.
Ar. Dr. Omer Shujat Bhatti **(Corresponding Author)**	Associate Professor & COD, Dept. of Architecture, School of Architecture & Planning, UMT, Lahore. omer.shujat@umt.edu.pk

Abstract: *The development of Lahore Ring Road (LRR) has significantly improved the regional transportation logistics; however, it is also a long-lasting 'grey barrier' which divides the peri-urban systems and breaks the micro-social fabric of adjoining residential clusters. Considering the dynamics of traffic throughput is the main approach to infrastructure assessment, this research uses a socio-ecological approach to assess the feasibility of "Green Bridging" as a restorative landscape intervention. This paper takes an infrastructural 'barrier effect' approach based on the secondary sources of systematic literature review and comparative case analysis to explore the infrastructural barrier effect, experienced through the urban fabric of Lahore. The study will map out key socio-ecological break points in the most affected areas of Lahore, such as Bahria Town, Lake City and Northern Loop, by comparing international precedents of vegetated overpass, namely successful models in Singapore and the Netherlands, with Lahore's micro-climatic and spatial variables. The evaluation is organised around three thematic headings: the mitigation of the Urban Heat Island (UHI) effect through the creation of local metabolic corridors; the reopening of the pedestrian permeability of fragmented communities; and the use of native plants for the bioremediation of vehicles exhaust. The results show that GIs are a multipurpose solution to conventional pedestrian overpasses that can serve as a social connective tissue as well as a biological conduit. The paper concludes with a vision and a strategy for introducing living architecture into the next stages of LRR development, and suggests a paradigm change to resilient and socially-engaged urban ecosystems.*

Keywords: Socio-ecological infrastructure, Barrier effect, Green bridging, Urban fragmentation, Lahore Ring Road (LRR).

INTRODUCTION & BACKGROUND

The Lahore Ring Road (LRR) is on track to be one of the most significant and defining megaprojects in its city's recent history by 2026. The LRR is designed to provide a high-speed, controlled-access orbital corridor that would wrap around the metropolitan core, helping to combat traffic gridlock in the inner city and improving regional transportation efficiency. The

corridor has been a great success, from a technocratic transportation perspective. It has converted the intra city mobility in a dramatic way; reduced vehicle's travelling time to Allama Iqbal International Airport; and spurred the real estate development on its outskirts. Most importantly, the LRR has increased spatial connectivity between high-density, quickly developing urban nodes and master planned enclaves, such as the Defense Housing Authority (DHA) Phase 13, Bahria Town, Lake City and Union Town.

A significant paradox is noted in the implementation of the LRR: the macro scale of vehicular connectivity and the micro scale of landscape fragmentation in today's civil engineering (Shah, Bhatti, and Ahmed 2023b). The corridor connects far-flung suburban nodes effectively, but is also a mono-functional impervious 'grey barrier' that also fragmentize and breaks up vulnerable peri-urban ecosystems and ripples long-standing socio-spatial networks. This uninterrupted stretch of asphalt and concrete results in what appears to be a discontinuity in the urban fabric, changing the LRR from an integrative infrastructural asset to an exclusionary boundary. Therefore, the present research suggests that when considering the large scale transportation infrastructure (Shah, Bhatti, and Ahmed 2023a), one should not just rely on the simplistic measures of traffic volume, vehicle speed and economic viability. Rather, a full analytical lens requires to be used, one that challenges systemic environmental degradation, and local social fracturing, caused by these interventions.

In the era of modern landscape architecture and urban ecology, landscape connectivity has become a component of landscape planning, with a particular focus on ‘green bridges' (also known as ‘vegetated overpasses', ‘wildlife crossings' or ‘eco-ducts'). These types of structures were originally conceived as a means to re-establish ecological continuity along the rural highways, as to simulate the continuous ground conditions of the landscape that connects to them along major transportation corridors. Green bridges create a living, structural continuum above high velocity roadways by supporting deep structural soil beds, native vegetation communities and hydrological matrices, which are normally not found in conventional pedestrian overpasses built of only steel and reinforced concrete (Ahmed et al., 2024).

Ecologically, green bridges directly tackle the issue of habitat fragmentation. Linear transport infrastructure functions as an absolute bio-barrier, creating large continuous ecosystems that are divided into patches which are sub-critical (Bhatti & Zahra., 2025). This ecological severance prevents local biota from moving, reduces the vectors for seed dispersal, and restricts genetic exchange, and thus decreases the evolutionary resilience of the remaining biota. Green bridges act as artificial bio-connectors, re-establishing landscape permeability to enable safe passage across high-speed corridors, while promoting macro-ecological balance.

Green bridges provide not only conservation benefits, but also important micro-climatic benefits in urban localities at risk from changing climatic conditions (Omer et al. 2024). Solar absorptive and sensible radiating surfaces of extensive dark asphalt in arid and semi-arid urban area such as Lahore make the Urban Heat Island (UHI) effect much worse (Salahuddin et al. 2024). These heat accumulations are broken up by vegetated overpasses. In addition to solar shading, the structural thermal mass and the active vegetative evapotranspiration act as cooling cells within a highly localized micro-climate over the ambient air temperature above the transport corridor.

Moreover, as a socio-anthropological perspective, green bridges revisit the concept of pedestrian infrastructure, which is experienced by humans. Typical pedestrian crossing points across high capacity expressways are often characterized by high levels of solar radiation, structural vibration and noise, all of which make for an environment that is inhospitable to non-motorized transport. In contrast, green bridges use thick vegetative barriers which acoustically protect the crossing from road noise and protect pedestrians from visual glare. The structures create a shaded, park-like amenity that

reimagines a hazardous crossing for human-scale mobility, active transport and adds spatial equity to communities torn apart by macroeconomic infrastructure developments (Bhatti et al., 2025).

The evolution of the Lahore Ring Road is also a reflection of the overall development of Lahore from a historically small city to a multi-nucleated metropolis. The LRR was originally conceived in the late 1990s and was to be the backbone of the region's effort to address sprawl and fast-track decentralization of the city (Shakeel et al., 2025), with large scale expansion phases planned for the 2010s and the mid-2020s. The project has been able to "manage" the rising volume of vehicles, the growing expectations of real estate prices on the periphery, but, in the process, has produced significant, unanticipated environmental and social "spillovers".

From an ecological perspective, the northern and eastern parts of the two loops penetrate rich agricultural soils, floodplains and important riparian habitats along the River Ravi. Millions of square meters of impervious concrete and asphalt have replaced alluvial topsoil, changing local hydrological cycles, storm water runoff and ability for natural groundwater recharge (Khan et al. 2024). This sealing of landscape has now ceased to be functional, and it has disrupted ecological processes, eradicated natural habitats and established an unnatural barrier for regional biodiversity (Iqbal et al., 2025).

At the same time, it is clear that the social costs of this infrastructural barrier are also very high along the peri-urban fringes and along historical settlements traversed by the northern loop as well as the newly advanced southern loops (SL3 and SL4) including Mehmood Booti and Baghbanpura. In the particular geographical areas, the LRR is a disruptive physical and psychological barrier. It suddenly cuts off the historical unified working classes from their farmland, local markets, schools, and families. The current pedestrian provision on these sections is very inadequate. The over-head steel bridges provided are spaced at too large a distance, are not accessible to everyone and do not provide any protection from the heat of Lahore in the summer. The absence of shaded and comfortable crossings further perpetuates an archaic urban planning philosophy that favours private vehicular transport over the dignity and safety of pedestrians and the accessibility of local spaces (Abbas et al., 2024).

The Lahore Metropolitan Area is at a crucial planning moment, with the engineering of the last segments of the western and southern parts of the Lahore Ring Road in progress. As it is now, the infrastructure is treated as a single-purpose system, separated from the natural environment and thus causing long-term degradation and social segregation (Aslam et al., 2024). A reactive and post-facto approach to mitigation is inadequate to deal with the problems of fast urbanization and climate change. Rather, a proactive approach must be taken, to include retrofitting of existing grey networks and incorporation of multi-functional ecological corridors into the future development of the LRR. Leaving the Ring Road in this condition would make it an ecologically inactive barrier, addressing macroeconomic transit requirements, while adding to the environmental and social vulnerabilities at the micro-economic level.

Green bridges at high-density rupture points have the potential to create an adaptive socio-ecological corridor that can transform the LRR from an exclusionary boundary into one. These vegetated connections can enhance the vitality of the surrounding ecosystem, bolster the thermal regime within the city and re-connect urban areas that are otherwise fragmented. In the end, the idea of urban infrastructure is not only reinvented as a static and hardened wall, but also as a dynamic and adaptive system that can enhance environmental resilience and social integration in today's urban context.

PROBLEM STATEMENT

Lahore Ring Road (LRR) is a fast moving, controlled access, orbital corridor that has triggered regional vehicular flow at the cost of landscape integrity in the city, resulting in the creation of a highly impermeable "grey barrier", which is mono-functional in nature and fundamentally affecting both landscape matrices and socio-spatial networks. Ecologically, it is a

massive non-porous asphalt and concrete infrastructure that breaks up large blocks of contiguous periurban habitat, cuts off regional bio-conduits and contributes to the Urban Heat Island (UHI) effect by retaining heat; socially it produces a significant rupture, physically separating vulnerable periurban villages and transitional settlements from necessary agrarian habitats and historic pedestrian routes. The engineering of the LRR is a significant technocratic accomplishment, but its physical implementation reveals a profound lack in the design of integrated and climate resilient infrastructure, in that pedestrian overpasses have been built to deal with the fundamental crossing problem, but are totally vulnerable to extreme thermal stress and ecological inactivity. This leaves a significant planning deficit, however, in current forms of South Asian urbanism, where there is no multi-functional, socio-ecological approach that is able to retrofit high-capacity transport corridors; and thus, if left unaddressed by strategic action such as 'Green Bridging', the LRR's ongoing expansion will continue to drive environmental degradation and spatial polarization.

RESEARCH OBJECTIVES

The main multi-disciplinary objective of this study was to explore the spatial, ecologic and structural feasibility of the green bridging interventions along the Lahore Ring Road as a tool to catalyze socio-ecological reconnection. In order to respond systematically to this mandate, the research was organized in the following two broad objectives:

1. Structural and spatial measures of ecological fragmentation, micro-climatic thermal accumulation and socio-spatial severance caused by the LRR in neighbouring urban fabrics.

2. To develop a replicable, multi-functional design planning framework to retrofitted living infrastructure at critical 'rupture points' along the corridor, based on the replicable parameters extracted from global precedents of green-bridges and tailored to the climatic conditions of Lahore.

RESEARCH SIGNIFICANCE

The work's theoretical and practical value is significant for the realm of landscape urbanism, environmental planning and infrastructure design in the Global South. This study breaks from the dominant engineering discourse in Pakistan that prioritizes the automobile, instead offering a comprehensive critique of the current paradigm, to provide an alternative, empirical approach that emphasizes ecologic resilience and human-scale mobility in the field of civil works. In terms of practice, the study presents a pragmatic context-specific approach to address some of the immediate urban challenges in Lahore, proposing and designing target-oriented green infrastructure measures that can reduce local thermal stress, absorb vehicular emissions through bio-remediation, and reinvigorate dignity, safety and comfort for the pedestrians.

The research is academically significant as it brings together the landscape urbanism approaches of the west and the east, and their socio-spatial realities, high densities and climatic vulnerability in a mega city in south asia. This paper does not see environmental conservation as in opposition to infrastructure development, but offers a conceptual approach to the possibility of turning infrastructure into an adaptive and living ecosystem. Finally, the results are presented as a reference document for urban administrators, policymakers, and civil engineers to provide an action plan for the city of Lahore to embrace a more inclusive, resilient, and sustainable urban model.

LITERATURE REVIEW

Rate of urban infrastructure and landscape fragmentation. Urban infrastructure and landscape fragmentation.

The landscape fragmentation associated with urban infrastructure, especially high speed highways has been a well-known concern for a long time. It has been coined as the barrier effect by Trocmé et al. (2023), which refers to the physical, ecological, and social disconnection caused by transportation corridors. Ring roads and expressways are frequently built in cities that are rapidly growing, transforming urban form and

ignoring ecological and human scale systems. In Road Ecology, Forman (2014) explains that highways create artificial edges where previously continuous landscapes existed. These borders create isolated habitat patches, which reduce the movement of species and the amount of gene flow. This isolation over time leads to a decrease in ecosystem resilience and biodiversity. This fragmentation is exacerbated in the context of cities in the Global South due to their urbanization, lax environmental controls and proliferation of slums in the vicinity of infrastructure corridors.

The effects on infrastructure are also important, as is fragmentation of the infrastructure on social impacts. Highways fragment and interrupt pedestrian networks and divide communities in terms of socio-economic status, which favors vehicle mobility. These impacts are especially pronounced in peri-urban areas, where rural areas, informal settlements, and gated communities are all present. This situation is typified by the Lahore Ring Road as a mobility corridor that at the same time separates communities and landscapes.

A dichotomy of socio ecological systems and landscape urbanism.

The theoretical framework of this study is based on Landscape Urbanism, where the landscape, rather than buildings or roads, is the key structuring force of the city. Today, cities face other issues, including climate change, environmental pollution, etc., that require new solutions, and these issues are in fact more urgent than those of the past (Waldheim, 2016).

There is no way to solve degradation and social inequality with traditional, road-based planning approaches.

Cities are defined in this context as a Socio-Ecological System (SES) where humans and environmental processes are interdependent. Ahern (2023) writes that infrastructure should be multi-functional – able to serve ecological processes, social interaction and climatic regulation – all at once. Infrastructure has thus become not a simple technical artefact but a metabolic interface that connects energy, water, motion and experience.

This lens will apply to highways and pose a question to traditional notions of roads as simply transport conduits. Rather, highways can be restyled as a hybrid space that can accommodate ecological corridors, public space and climate responsive design. Within this discourse, green bridges are being developed as spatial solutions to physically and conceptually reconnecting socio-ecological systems that have become fragmented

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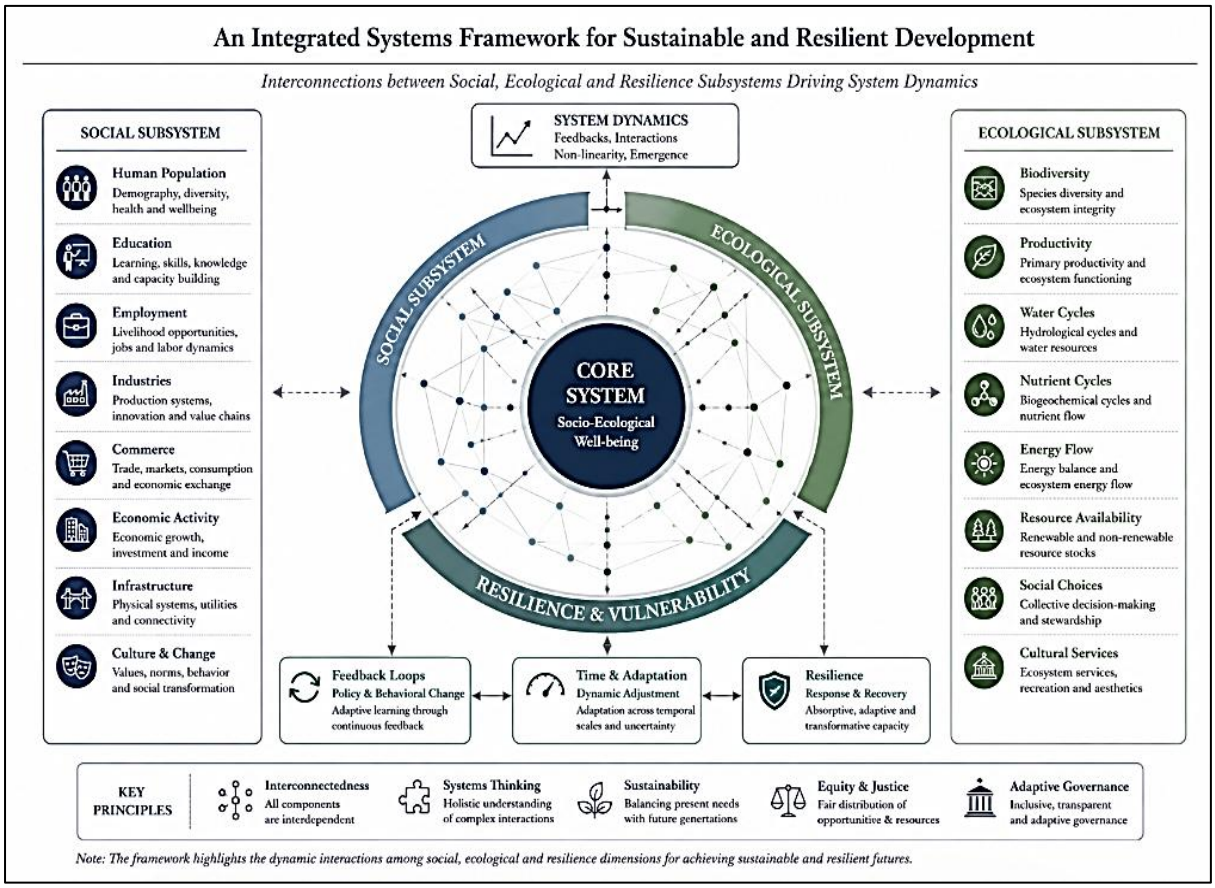

Figure 2.1: Interconnectedness of Socio-Ecological Systems, showing how human society and the natural environment interact and influence each other.

Green Bridges as Living Infrastructure

The term "green bridges" or "eco-ducts" is frequently used and first appeared in Europe as structures built to enable safe passage across highways for animals. In the course of years their tasks have grown to respond to more comprehensive environmental and urban issues.

Van der Grift et al. (2016) distinguish three main typologies for green bridges:

Landscape Bridges, simulating surrounding ecosystems, and creating complete habitat continuity. Multi-functional Bridges, that allow wildlife movement and human use, are sought after.Multi-functional Bridges, allowing wildlife movement and human use, are desired.

Retrofitted Green Crossings are modifications of grey infrastructure made more environmentally friendly with vegetation and soil systems. Studies around the world have proven that green bridges decrease wildlife–vehicle collisions, restore habitat connectivity and enhance ecological resilience. Recent literature, however, highlights that their role goes beyond the ecological realm. Human design of green bridges improves walkability, decreases environmental dissatisfaction and brings public green spaces into infrastructure-dominated spaces. Local adaptation is especially important in semi-arid cities, like Lahore. According to Mumtaz (2022), native, drought-resistant plants are crucial to long-term performance. Some species like Acacia nilotica and Cassia fistula are also capable of providing canopy cover and surviving extreme heat, and they also contribute to biodiversity in the local area—this was a point made by the authors that green bridges need to be flexible and adapt to

the regional climatic conditions rather than be imported.

Green Infrastructure as a solution to the urban heat island effect.

Lahore is facing an increasing challenge due to its Urban Heat Island (UHI) effect, which is caused by the large surface area of asphalt and concrete, which contributes to raising ambient temperatures. Rana et al. (2021) show that highway corridors do not contribute to the overall thermal stress equally, instead they result in significant localized thermal stress in the peri-urban areas which are lacking of tree cover. Vegetation is one of the key components for thermal regulation identified in literature on BGI. Bowler et al. (2010) noted that urban greening has a cooling effect on the surface and air due to its shading and evapotranspiration effects. Such cooling benefits are greater on taller structures like bridges, because they are positioned above high-energy road surfaces. Green bridges consequently serve as a localized cooling system and contribute to the comfort of pedestrians as well as to the decrease of the heat accumulation over major highways. In the context of cities that are vulnerable to climate change, this thermal efficiency reinforces the need to integrate green infrastructure into the urban transport planning process.

Key Global Precedents

Rather than presenting extensive descriptive case studies, this section synthesizes lessons from selected global precedents that demonstrate the ecological, social, and climatic potential of green infrastructure.

Table 01 Case Studies

S.No	Title	Images	Details
01	**Eco-Link@BKE, Singapore**	 	**Eco-Link@BKE is considered a best practice example of a purpose built ecological overpass that achieves a successful link between transportation infrastructure and biodiversity goals. The bridge will be built over the main expressway, providing a new link between two nature reserves and the restoration of landscape connectivity between different habitats. It has large soil depths and a design that includes special structural systems that can accommodate mature vegetation and/or natural ecosystem processes. Ecological monitoring after construction has shown the**

			project is having measurable impacts on wildlife–vehicle collisions, and that it is being used by a variety of faunal species. The project delivers strong evidence on how ecological bridges can be highly effective biological corridors – even in highly trafficked urban environments – and can support wildlife movement and maintain habitat connection.
02	**Birkenhead Park, United Kingdom**		**Birkenhead Park, designed by Joseph Paxton, is considered to be a much studied work in the development of the modern public park movement. The park was designed in the era of the Industrial Revolution, and was designed as a socially progressive intervention to overcome unequal access to good quality green spaces. One of the most interesting features of Paxton's design approach was his creative mixing of landform manipulation and earth modeling to serve as a buffer to noise and visual intrusion from other urban elements. These principles can be very useful for modern green bridges, where the topography and the plants are utilized to shield people from the surrounding transport facilities. In addition, Birkenhead Park serves as an example of the high economic and social return of the landscape-led**

			approach to urban development, and of how investments in green infrastructure can add value to the land, and to urban life.
03	**Seoullo 7017, South Korea**	 	**Seoullo 7017 is a good example of adaptive reuse which has transformed an outmoded transportation system into a public place with multiple functions. The project reconnected previously isolated urban neighbourhoods by transforming an old highway overpass into a pedestrian-friendly green corridor, while also improving the environmental quality and thermal comfort in an urban built-up environment. Seoullo 7017 serves as a lively public space as well as an ecological stepping-stone corridor supporting biodiversity in the city. The project underscores the transformative power of retrofitting and repurposing existing infrastructure assets as a viable and sustainable alternative to new construction, highlighting the potential for reuse of underutilized urban infrastructure to create socially, environmentally and economically valuable public space.**

The reviewed literature shows that highways are physical and symbolic barriers in urban systems. Green bridges and green infrastructure interventions are proven approaches worldwide to reduce ecological fragmentation, social isolation and climatic stress. Most current studies, however, are conducted in contexts from the developed world, where there is a robust regulatory regime and financial resources. A huge challenge is to implement these principles in the context of high-density, semi-arid South Asian cities, especially when retrofitting existing orbital highways where land acquisition and road alignment is already determined. This void directly reflects the current study that offers the Lahore Ring Road as a benchmark for context-sensitive green bridging in a fast urbanizing megacity.

RESEARCH METHODOLOGY

The methodological approach used for socio-ecological feasibility of green bridges implementation on the Lahore Ring Road (LRR) was as follows. The choice of the qualitative research approach was justified for the following reasons: theory building and theory testing were part of the study, and the research was conducted in a theoretical and spatial setting. This way, an in-depth analysis of the relationships between infrastructure, ecology and society is possible which cannot be expressed by quantitative measurements alone.

The methodology is organized to combine all the relevant theoretical knowledge and explain it.

Research Design

This study is descriptive and exploratory research. It is descriptive and addresses current conditions that have resulted from the LRR, especially how the LRR has created ecological fragmentation and limits the movement of people. At the same time, it is exploratory in its exploration of the potential green bridging as an untapped infrastructural solution in Pakistan. The two part design allows for the documentation of existing socio-ecological issues, and the creation of context-specific design and planning solutions.

Methodological Framework

The research process consists of three steps. All the phases are geared to each other to provide conceptual clarity and analytical continuity.

Phase I:

The first phase aims at laying out the theoretical background of the study by conducting a systematic review of the academic literature dealing with the following:

Road ecology and fragmentation of infrastructure

Explore the concept of landscape urbanism and socio-ecological systems. Discuss landscape urbanism and socio-ecological systems.

Urban Heat Island mitigation by using green and blue–green infrastructure.

This synthesis offers the conceptual frame for assessing the Lahore Ring Road as a socio-ecological system and not as a transport-only infrastructure.

Phase II:

The second part consists of the analysis of the selected international case studies of successful implementation of green infrastructure in transportation systems. The primary purpose of these case studies is to act as a benchmark, so that transferable principles can be identified, but not simply replicated. The cases were assessed on common criteria, such as ecological performance, social impact, climatic responsiveness and implementation feasibility. This comparative approach helps to make lessons learnt from the experiences of other countries relevant to the context of Lahore and its unique climatic and urban conditions.

Phase III:

The last phase uses the literature and literature analysis of case studies to the spatial reality of the LRR. The Ring Road was analysed with secondary spatial data and land-use mapping to identify socio-ecological disruption areas

where infrastructural fragmentation is at its peak. In this study, these areas are referred to as "rupture points," or areas of high ecological severance and social disconnection. Identification of rupture points allows for targeted interventions via green bridges, as opposed to one-size-fits-all and symbolic interventions.

Data Collection Methods

There are no primary field surveys or experimental tests in this research, but only secondary data sources. These sources were chosen to provide academic credibility and that they were relevant. Peer-reviewed journal articles, books and conference proceedings were obtained from Google scholar, Research Gate and Science Direct. The literature search was conducted using the keywords such as green bridges, landscape urbanism, road ecology, and urban heat island. Official reports and planning documents were reviewed from: Lahore Development Authority (LDA) & Lahore Ring Road Authority (LRRA). These documents contained data on road alignments, expansion phases, land-use interfaces, and environmental issues of concern with the LRR. Selected international precedents were reviewed such as Eco-Link@BKE (Singapore); Birkenhead Park (UK); Seoullo 7017 & (South Korea). Both technical feasibility and long-term performance considerations were provided by these sources.

Case Study Selection Criteria:

Case studies were chosen for the following reasons:

- Fragmentation caused by transportation infrastructure projects are the focus of functional relevance.
- Demonstrated Impact: Evidence of ecological, social or climatic benefit
- Energy Efficiency: Economics of production with respect to energy efficiency

The Socio-Ecological Lens is the Analytical Framework.

A Socio-Ecological Systems (SES) framework was used to analyze data. This approach accounts for the interdependency of environmental processes and human activity, and is especially appropriate for assessing infrastructure as a multi-functional system.

There were two main types of variables used:

Ecological Variables

- Movement and connectivity of habitats and species are considered.
- Thermal regulation, thermal mitigation potential
- Bio-remediation through vegetation

Social Variables

- Pedestrian permeability/accessibility
- Lessening of dissatisfaction in the environment (noise, heat, and visual stress)
- Improved public and recreational benefits

This analytical framework allows for simultaneous assessment of human and ecological benefits.

The research has some limitations due to its qualitative and literature based nature. This study does not contain primary data, including on-site temperature readings, tracking data from wildlife use, or pedestrian usage surveys specific to the LRR. These constraints can be overcome, however, by adopting the validated international case studies, detailed spatial documentation and established environmental research applicable to the climatic conditions of Punjab.

RESULTS AND DISCUSSION

Socio-Ecological Impacts along the Lahore Ring Road is an overview of the impacts on socio-ecological systems along the Lahore Ring road.

The analysis undertaken on the Lahore Ring Road (LRR) shows that the impacts of the LRR are not uniform but rather unevenly distributed. The Ring Road has a negative effect on regional mobility, but worst of all, it does so at certain points where it crosses sensitive ecological systems or dense human population. This study specifies these areas as socio-ecological rupture locations, areas where the Ring Road causes its greatest severance of ecology and disconnection of social. The identification of the rupture points enables the implementation of targeted measures for greening as a bridge between the opposing interests instead of general or symbolic ones.

Three main typologies of ruptures were identified along the LRR based on land-use, environmental sensitivity and settlement morphology:

- Riparian/ecological breaks
- Ruptures – social or pedestrian
- Blue–green infrastructural intersections

Riparian Rupture: Northern Loop near the Ravi River Results

The LRR crosses floodplains and riparian systems along the northern loop of the Ring Road, especially in the area of the crossing from the Ravi River, where the river was originally part of a continuous ecological unit. The road-building, in turn, has created barriers to the birds, small mammals, and pollinators' ability to move between the river corridor and adjacent farmland. Impervious road surfaces have also replaced permeable soils, which has affected natural hydrology and led to higher runoff and loss of floodplain ecological function.

This break follows the precedent set by Eco-Link@BKE and will involve providing a Type A green bridge, a wildlife friendly ecological overpass built to provide habitat connectivity over the building site rather than access for people. The vegetated bridge at this site would be an extension of Ravi River landscape and would connect the habitats which are broken in between the Ring Road.

They could incorporate native riparian plants to benefit avifauna and pollinators and to enhance floodplain resiliency. This would help to re-establish ecological continuity in the Ravi River corridor and make it a vital part of Lahore's green–blue infrastructure instead of just a broken fragment.

Social Rupture, has produced the following results:

The LRR is a clear physical and psychological barrier to pedestrians in the southern parts of the Ring Road, especially in Bahria Town, NFC Phase 2 and Maraka. Agricultural land, markets and neighbouring settlements are isolated from residential communities. The pedestrian bridges in these areas are narrow, exposed, thermally uncomfortable and not used on a regular basis. This means that many informal and unsafe road crossings are seen, reflecting unmet pedestrian need.

This rupture can be dealt with by introducing Type B multi-functional green bridges based on the principles of Birkenhead Park and Seoullo 7017. The bridges are designed as linear public spaces, rather than a traditional pedestrian overpass, with a focus on comfort, safety, and social interaction. These bridges are introduced to make the crossing of the Ring Road a dignified and climate-friendly experience thanks to soil depth, shade trees, seating and visual buffers. These interventions directly reopen the pedestrian permeability and minimize the dissatisfaction with the environment due to noise, heat, and visual stress. This perspective puts infrastructure in a different light than as a social barrier, especially in peri-urban settings where walking has been a central part of people's lives.

Blue–Green Rupture: Canal and Drainage Intersections Results

The LRR interferes with water flow at intersections where it crosses canals, irrigation distributaries, and drainage channels, like the

BRB Canal, affecting both the water systems and ecological flow. There are locations where environmental stress takes place because of heat buildup, polluted runoff and low public access to water bodies. These sites are appropriate for Type C blue, green green bridges, incorporating vegetation with water-sensitive infrastructure, inspired by the project Ecductor in Mexico City. These bridges can integrate bio-swales, constructed wetlands and rain water catchment systems to help filter road traffic runoff before it reaches ground water systems and/or canals. They promote the reintroduction of water into the pedestrian realm, reduce and enhance the microclimatic cooling effect, and improve the quality of the water. Blue –green bridges provide a multifunctional answer to environmental stress in a city where water shortages and monsoon inundations are a problem.

Movement

Application of the Agri-tecture Framework Results

The Agri-tecture Framework Results has been applied in the following way:

Research on landscape precedents worldwide identifies the successful model of agri-tecture, a strategy that integrates landscape systems seamlessly into the design of structures. The green bridges can play ecological, social and climatic roles when using this framework on the LRR. The study suggests xeriscaping techniques with plants that are native and drought-tolerant like Acacia nilotica, Cassia fistula and Bougainvillea. These species are well suited to the semi-arid climate of Lahore, have a high canopy cover, and have low irrigation requirements. Results from similar studies have shown that vegetated structures can lower the surface temperature 8–10°C from exposed asphalt. This reduction makes pedestrians more comfortable in the extreme summer weather in Lahore, and provides less heat-related stress on the infrastructure.

One of the main issues with implementing a green bridge is the perceived economic feasibility. But the analysis of case studies shows that the use of green infrastructure can be economically sustainable when it is part of a city development plan.The Birkenhead Park model is an example of the success of the land value capture funding model. In Lahore, this implies that high-value developments that are adjacent to the Ring Road, like DHA and Bahria Town, could be involved in co-financing Green Bridges via public–private partnerships (PPP). Green bridges directly support the real estate value and livability indexes through walkability, heat stress reduction and visually quality improvements. Developers thus have a concrete interest in contributing to their development and ongoing maintenance.

Demonstrating technical challenges and mitigation strategies. Identifying technical challenges and mitigations.

There were a number of technical difficulties identified during analysis:

- Water Scarcity: Solved by implementing drip irrigation with water from rain harvesting, thus establishing a closed water circuit.
- Structural Load: Controlled with lightweight soil substrates, reinforced concrete box-girder or arch structure, in combination with geo-grid reinforcement.
- Vegetation Resilience: Achieved by selecting native species that have deep root systems and produce a lot of shade.
- Noise Mitigation: accomplished with earth berms and vegetated buffers similar to what Paxton uses to model soils.

These approaches demonstrate the feasibility of green bridges within structural and climatic limits of the LRR.

The study concludes that although the Lahore Ring Road (LRR) has brought about a shift in the regional mobility landscape, it has become

the source of institutionalizing an ecological and urban divide. The existing 'grey infrastructure' approach has been based on the dominance of vehicular circulation at the detriment of the socio-ecological landscape, which has led to the fragmentation of habitats, intensification of urban heat island and the disconnection of pedestrian spaces between traditional towns and modern gated developments. Current mitigation measures, such as ornamental roadside plantings and steel pedestrian bridges, are superficial, the study finds. They do not take into account the basic continuity of nature and the human thermal comfort. This research argues for this, however, by drawing on the global precedents such as the High Line or Eco-Link@BKE, the LRR can be rethought through Landscape Urbanism. To change this, Green Bridges are introduced, transforming the LRR into a "living connector. This shift is crucial for Lahore to achieve its historic status as "City of Gardens" and to develop a multi-functional and climate resilient transportation system.

SUMMARY OF FINDINGS

The results show that socio-ecological negative impacts of Lahore Ring Road can be identified and addressed. When the right strategic green-bridge interventions are put in place, rupture points can be transformed into areas of reconnection. The international precedents analysis shows that effective landscape and infrastructure interventions exist which can provide the basis for the development of the Lahore Ring Road (LRR) green bridge project, while addressing key environmental, social, ecological and economic issues. Contemporary urban environments have one of the most urgent issues of urban heat island effects. The various elements of the proposed LRR response are inspired by the High Line, and focus on the inclusion of a dense vegetative canopy that can provide significant shade, microclimate, ambient cooling, and thermal comfort to the users. Therefore, these vegetation-based approaches not only help to create environmental sustainability but also enhance the overall quality of urban public areas.

Social connectivity aspects of Birkenhead Park are used as an example of the importance of designing inclusive and accessible green infrastructure to encourage interaction amongst diverse groups of users. In this sense, the LRR proposal promotes the development of multifunctional pedestrian bridges, which are not only crossing points, but also places of recreation, socialization and active mobility. These can be interventions that can bring together communities that have been physically split by large transportation corridors.

The other basic goal of the planned intervention is ecological continuity. The value of wildlife-oriented bio-corridors for the restoration of habitat connectivity in landscapes with fragmentation is illustrated through lessons learned from Eco-Link@BKE. The use of such ecological design concepts and principles in LRR would enable the movement of species, contribute to the conservation of biodiversity and improve the resilience of ecosystems in the urban environment. Moreover, the successful funding mechanisms of the Birkenhead model offer useful guidance for implementation of projects. The establishment of Public–Private Partnership (PPP) frameworks with land value capture mechanisms can create a sustainable financial resource and long-term economic viability. These global lessons offer a solid baseline for the LRR proposal, which will incorporate environmental performance, social inclusion, ecological restoration, and financial sustainability – in a holistic and evidence-based planning process.

RECOMMENDATIONS

The proposed Lahore Ring Road Green-Bridging Strategy is oriented towards creating ecological corridors in a context-sensitive and multi-functional approach for better ecological connectivity, sustainable mobility and environmental resilience in this vibrant city. It suggests various use typologies of bridges based on the surrounding land uses in the area

to be implemented by the Punjab Highway Authority (PHA) and Lahore Development Authority (LDA). Biological green bridges to restore connectivity and support wildlife movement should be built in rural and peri-urban areas, especially along the northern and southern loops, using native plants and noise barriers. On the other hand, pedestrian friendly green bridges should be installed in places like DHA and Bahria Town, which should provide shaded and green pathways for walking and cycling. The strategy also recommends incorporating Bio-Swales and Constructed Wetlands for the purpose of naturally filtering the road runoff before it reaches the water bodies and groundwater systems in the vicinity of Lahore to mitigate the water related challenges being faced by the city. The implementation of a Landscape Connectivity Index (LCI) into EIAs to provide sufficient ecological crossings along highway corridors is also an element of institutional support. Community involvement is also highlighted via co-management arrangements involving local people in the management of vegetation to facilitate social ownership that will help to lower operational costs. Last but not least, the use of camera traps and acoustic sensors is encouraged in order to monitor biodiversity and ecological performance and refine the designs of the bridges over time, based on evidence.

FUTURE SCOPE OF RESEARCH

Although green infrastructure has become a recognized vision of sustainable urban intervention, a number of key research areas need to be further examined to make the transition from theory to implementation. First of all, the effectiveness of green bridges in decreasing urban temperatures, improving thermal comfort and increasing the carbon sequestration potential need to be provided by quantitative microclimate modeling through advanced simulation tools like ENVI-met, to provide empirical evidence. Second, ecological recovery, connection and population dynamics of species following green infrastructure interventions should be measured using longitudinal biodiversity monitoring along ecological corridors, especially within the Ravi River region, to look at long-term ecological recovery. Further, there is a need for robust psychosocial impact assessments to assess the impact that being near green-retrofitted infrastructure will have on the mental health, social interactions and sense of place of residents. Life Cycle Cost Analysis (LCCA) should be developed to account for all direct and indirect benefits as well, such as reducing health care costs from heat stress mitigation, enhancing environmental quality, and improving surrounding property values. In addition, it is important to investigate smart water management systems that enhance the sustainability of green bridges in the context of the semi-arid conditions typical to that of many South Asian cities, including the use of innovative xeric-hydroponic techniques and closed-loop irrigation systems. These research streams will add to the body of evidence to inform planning, design, evaluation, and management of green infrastructure projects.

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