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AGICore: A Traceable, Structurally Explainable Computational Framework for Assessing Nature-Based Solutions Under Urban Heat Risk

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Abstract

This study frames the concept of a "core code" of complex adaptive systems within a scientifically testable approach, rather than relying on abstract and difficult-to-verify assumptions. Urban heat island (UHI) risk and nature-based solutions (NbS) are examined through the AGICore framework, which provides a traceable and structurally interpretable analytical approach. AGICore defines three recurring components across scales: regulation (feedback and stability), agency (goal-oriented action), and information (costs of measurement and processing). These components are evaluated within thermodynamic and information-theoretic constraints. Instead of proposing a single final equation, the framework introduces a reduced dynamic representation based on observable variables and a traceable decision structure. The framework is applied to urban regeneration areas in Ankara (NMURP and NAURP) using Urban Heat Island Effect Ratio (UHIER) and land surface temperature (LST) data for 2005–2022. Findings from Ozenen Kavlak et al. (2025) are reinterpreted within the AGICore perspective. Results indicate an overall decline in UHI intensity, while localized heat accumulation persists in completed and high-density subregions. This suggests that thermal outcomes of urban regeneration vary depending on morphology, surface impermeability, and green infrastructure composition. The main contribution is to move beyond treating UHIER as a single indicator by emphasizing spatial heterogeneity and mechanism-based evaluation. This approach highlights that NbS effectiveness should be assessed not only by increases in green space but also through their interaction with surface energy balance and spatial intervention components.

Keywords: *Urban heat island (UHI), Urban regeneration, Nature-based solutions (NbS), Remote sensing (LST), Local climate zones (LCZ), Reproducibility*

1. Introduction

Urban heat island (UHI) has increasingly become a systemic risk for cities in the context of climate change. The IPCC Sixth Assessment Report (AR6) indicates that urban areas exhibit higher temperatures than their surrounding rural environments, and that this difference becomes particularly pronounced during extreme heat events (IPCC, 2021). Rising temperatures not only affect thermal comfort conditions but also place direct pressure on energy demand, infrastructure load, and public health. Indeed, the impacts of UHI on energy consumption, mortality, and inequality have been extensively addressed in the literature (Oke, 2002; Rizwan et al., 2008; Hajat et al., 2010). In this context, urban regeneration and redevelopment projects are often presented with claims of environmental performance, and nature-based solutions (NbS) are considered important tools for heat mitigation. The effects of NbS on the urban microclimate are explained through shading and evapotranspiration mechanisms (Bowler et al., 2010; Ziter et al., 2019). However, there is a significant methodological limitation in the evaluation of these effects. A substantial portion of existing studies relies on area-wide averages and addresses spatial heterogeneity only to a limited extent. The Local Climate Zones (LCZ) approach developed by Stewart and Oke (2012) clearly demonstrates that urban heat is not a homogeneous phenomenon but includes texture-based differences. This situation may lead to transformation projects being evaluated as "successful" at the overall level despite producing thermal intensification in certain sub-regions. Similarly, the causality literature emphasizes that inferences based on spatial averages carry the risk of ecological fallacy (Pearl, 2015). Therefore, the main issue is not only to measure temperature change but also to determine under which structural constraints and spatial conditions interventions are effective.

At this point, the "core" approach becomes relevant. The idea of a "core code" can be interpreted in two different ways. The first approach aims to explain complex systems through a single equation, whereas the second focuses on identifying recurring necessities and measurable constraints across different systems. This study adopts the second approach. The aim is to explicitly define the recurring regulatory constraints in systems governing urban climate and disaster risk. In this context, the "core" is not used as a claim of a universal formula, but rather as an expression of structural necessities that must be considered together in the assessment of urban heat risk. In line with this approach, the study proposes a framework called AGICore. AGICore is based on the integrated and balanced evaluation of Regulation–Agency–Information (R–A–I) components. The objective is not merely to define these concepts but to establish the relationships between them explicitly. Regulation is associated with feedback mechanisms that sustain system stability and is defined through the principle of "requisite variety." As stated by W. Ross Ashby (1956), the internal control capacity of a system must be sufficient to counteract external disturbances. This principle applies across different scales. While biophysical processes constrain the system at the planetary scale, regulation at the urban scale operates through surface energy balance (Oke, 1982; Voogt & Oke, 2003). Agency, in this study, is addressed within a technical framework beyond its everyday institutional meaning. It refers to a system's capacity to select actions within its state space and includes not only reactive responses but also the ability to produce targeted interventions. At the urban scale, this capacity materializes through decision-making and implementation processes. Planning decisions, design standards, maintenance regimes, investment choices, and control mechanisms constitute the main components of this capacity. In the AGICore approach, agency is not treated as a random action space but as an optimization process operating within a perception–action–learning loop. Therefore, agency represents the entirety of managerial and design capacity shaping urban morphology, levels of

impermeability, and green infrastructure networks. Information, in this framework, is defined as a process constrained by physical limits and costs. It is well established that measurement, data processing, and memory updating processes carry an energy cost (Landauer, 1961). In addition, the limited capacity of representation and transmission introduces constraints within the perception–transmission–processing chain. These constraints directly affect the effectiveness of regulation. When information is insufficient or cannot be processed effectively, regulatory mechanisms cannot be translated into action, and the intervention capacity of agency becomes limited.

Within this scope, the AGICore framework not only brings together Regulation–Agency–Information components at a conceptual level but also treats them as a system operating under specific constraints. This structure is defined through four fundamental constraints: the thermodynamic cost of information processing, the capacity limits of representation and transmission, the principle of optimization within the perception–action–learning loop, and the safe operating space approach defining multi-scale stability. These principles are not considered as analogies but as limiting conditions. In this context, "cost" refers to the inevitable energy and capacity requirements of information production and processing. Information processing occurs on a physical substrate, and irreversible operations are associated with heat generation (Landauer, 1961). Regulation operates through representation processes, which are related to encoding, where capacity limitations become decisive. As expressed in the Shannon–Weaver framework, the relationship between channel capacity and source entropy defines the upper bound of transmission and representation processes (Shannon & Weaver, 1949). These limitations apply not only to communication systems but to all processes from perception to decision-making. When capacity is insufficient, regulatory mechanisms cannot become operational. Agency, in turn, is addressed as an optimization problem under these constraints. A common theme across different theoretical approaches is that systems regulate their behavior according to specific objective functions (Friston, 2010). This allows agency to be associated with measurable goals and expands regulatory processes through a prediction–error–update loop.

The problem of multi-scale stability is similarly addressed at the planetary scale. The Planetary Boundaries framework shows that the Earth system operates within a safe operating space defined by biophysical processes (Steffen et al., 2015). This approach demonstrates that regulation is not only a local issue but also a multi-scale boundary problem and introduces the concept of "control variables" into a methodological framework. At this point, AGICore does not aim to reduce all scales to a single equation but proposes a common technical approach: representing nonlinear processes through approximately linear operators in the space of observables. In this context, the Koopman approach and its practical implementation through Dynamic Mode Decomposition (DMD) become relevant. The theoretical connections between these approaches are clearly discussed in the literature (Tu et al., 2013). Within this framework, regulation, agency, and information are defined as observable variables, dominant system behaviors are extracted through this representation, and control logic is constructed accordingly. Overall, the AGICore approach is structured around four key principles: cost, capacity, optimization, and stability. Accordingly, the analysis proceeds in three stages: establishing conceptual clarity, defining measurable indicators and methodological structure, and developing falsifiable hypotheses along with application classes. The fundamental assumption of this approach is that persistent systems—whether biological, biophysical, or institutional—must organize regulation and agency together under the constraints of information cost and capacity limits. At the urban scale, agency is therefore operationalized as decision and implementation capacity, intervention repertoires are linked to spatial outputs, and translated into measurable hypotheses.

The aim of this study is to define AGICore not as a single ultimate equation but as a framework that identifies recurring fundamental constraints across different scales in a measurable and evidence-based manner. The objective is to transform these constraints into a verifiable and falsifiable research approach. In this context, the scope of the study is addressed at two levels. The first level involves the theoretical grounding of Regulation–Agency–Information components within the frameworks of thermodynamics and information theory. The second level consists of operationalizing this theoretical framework at the urban scale. This operationalization process involves linking the Urban Heat Island Effect Ratio (UHIER) and heatwave risk with NbS interventions through measurement, inference, and control processes. In this process, the findings obtained from the study conducted by Ozenen Kavlak et al. (2025) are re-evaluated within the AGICore framework. In that study, UHIER and LST analyses are addressed together with land cover, urban morphology indicators, and stage-based heterogeneity. The assessment of urban heat risk is not limited to the production of temperature maps. The type of data used, its resolution, temporal coverage, and processing workflow are also integral parts of the analysis. At this point, the AGICore approach adopts the explicit definition of the data processing workflow and the traceability of all computational steps as a fundamental principle. Accordingly, not only the resulting maps but also the computational processes through which these results are produced are treated as shareable and auditable research objects. The reproducibility of scientific studies is considered a fundamental requirement in contemporary methodological literature (Peng, 2011; Wilkinson et al., 2016). The originality of this study does not lie solely in bringing together different strands of literature. It also lies in integrating traceability and reproducibility principles as inherent components of the methodology. This approach offers three main contributions to the literature. First, it repositions UHIER analysis beyond a comfort-based indicator within a resilience framework. Second, it makes stage-based heterogeneity visible, enabling the questioning of area-wide generalizations. Third, it provides a transferable application framework that evaluates the effects of NbS interventions in relation to contextual factors such as morphology, impermeability, and the continuity of green infrastructure. Within this context, the proposed framework offers a mechanism-oriented and auditable analytical standard that goes beyond average-based approaches in evaluating the environmental performance of urban regeneration projects. This approach provides a comparable and reproducible evaluation ground in which UHIER and NbS effects can be tested under contextual conditions. The methodological structure proposed by AGICore is not limited to producing results specific to a single case study. It also offers a transferable research framework that allows similar interventions to be tested in different cities.

2. Methodology

This section places the conceptual backbone of AGICore within a concrete evidence structure in the context of city–disaster–NbS. Rather than producing results through a single metric (UHIER), the design approach is based on the joint consideration of measurement, inference, and control components. Accordingly, the analysis is structured along three main axes: (i) observables and the data pipeline (Information), (ii) the mechanism level through surface energy balance, land cover, and morphology (Regulation), and (iii) intervention heterogeneity and the operational limits of agency (Agency). This structure aims to evaluate the thermal change observed in urban regeneration areas not merely as increase or decrease, but as a mechanism pattern associated with intervention components. The reference dataset used in this section consists of the LST–UHIER outputs presented in Ozenen Kavlak et al. (2025). The aim is to reinterpret

these findings within the AGICore framework and to make the inference process explicit by relating spatial heterogeneity to the mechanism level.

2.1. UHIER as a Reference Scenario for AGICore

In this study, UHIER is addressed as a reference scenario within the AGICore framework. UHIER is considered not merely as a descriptive thermal pattern, but as a systemic risk that can be evaluated together with measurable physical mechanisms, intervention differences, and data-based monitoring capacity. In this respect, this section serves three main functions: to establish the position of UHIER in the disaster context through the literature, to explain the mechanism level through surface energy balance and land cover–morphology relations, and to relate these mechanisms to the Regulation–Agency–Information framework. This approach transforms UHIER from being only an output variable into a structurally interpretable analytical domain. In addition, UHIER is addressed not as a secondary comfort problem but as a systemic stress factor that is becoming increasingly decisive in the disaster portfolio of cities. The IPCC AR6 report clearly shows that urban centers exhibit higher temperatures than surrounding areas (IPCC, 2021). Similarly, the World Health Organization emphasizes that increasing heat waves become even more severe in urban centers due to the UHIER effect. This framework justifies the selection of UHIER as the reference scenario in the methodology.

From the perspective of AGICore, UHIER provides an application domain in which the Regulation–Agency–Information components can be observed simultaneously. Regulation is defined through surface energy balance and microclimatic feedback mechanisms. Shading, evapotranspiration, surface albedo, wind flows, surface roughness, and anthropogenic heat emissions interact together. Agency refers to the institutional and managerial capacity that determines how and through which combination these components will be changed. Planning decisions, design standards, maintenance processes, and control mechanisms are the concrete elements of this capacity. Information is not limited merely to data availability. It is addressed as a production–transmission–processing process that includes early warning systems, thermal mapping, and post-intervention monitoring processes. This process is subject to physical and capacity-related constraints. Landauer's principle of irreversibility (Landauer, 1961) states that information processing carries an energy cost, while Shannon's capacity limit (Shannon & Weaver, 1949) defines the theoretical limits of transmission processes. For this reason, the compatibility between data intensity and decision capacity is accepted as a methodological evaluation criterion.

Another critical issue in the UHIER scenario is the differentiation of urban typology. The heat island does not emerge on a single urban structure, but on a mosaic formed by different morphological and land cover components. For this reason, LCZ classification is one of the main components of the methodology. This approach, developed by Stewart & Oke (2012), makes it possible to differentiate urban heat variations spatially. The use of LCZ both reveals how regulatory capacity varies across different texture types and provides comparability among different cities. Within this framework, observable findings are addressed through a multi-layered structure. The first layer consists of thermal indicators such as LST, air temperature, humidity, and wind. The second layer includes land cover and morphology components. Impervious surface ratio, NDVI/EVI, LCZ classes, and urban form indicators are included in this group. The third layer covers social vulnerability and exposure indicators. The joint evaluation of these layers makes it possible to address UHIER not only as a physical phenomenon but also as a risk-based system. The remote sensing literature supports the information dimension of this approach. It is well known that thermal remote sensing techniques are widely used in UHIER analysis (Voogt & Oke, 2003). NDVI is one

of the main indicators used in such analyses to reveal the relationship between vegetation cover and temperature (Weng, 2004). Nevertheless, there are limitations in interpreting such relationships directly as causality (Pearl, 2015).

Within this framework, NbS is treated as the concrete counterpart of regulatory mechanisms. NbS interventions are evaluated through processes such as shading, evapotranspiration, surface properties, and airflow. This approach makes it possible to address NbS not only through increases in green area, but together with its effects on surface energy balance. The literature has shown that these effects are measurable. For example, it has been reported that park areas reduce daytime temperatures by approximately 1 °C on average (Bowler et al., 2010). However, it is also emphasized that this effect is context-dependent and that the nighttime effect may remain limited (Ziter et al., 2019). This situation indicates that regulatory mechanisms must be diversified. The principle of variety expressed by W. Ross Ashby (1956) supports the necessity of diversifying the intervention repertoire at the urban scale.

Another important issue in UHIER analysis is the consideration of regime behavior beyond average values. Situations such as the disappearance of nighttime cooling may create critical impacts on health and energy systems. For this reason, the AGICore approach also includes dynamic analyses based on time series. In this context, dominant modes of system behavior are examined using Koopman/DMD methods. In addition, the validation process is not reduced only to statistical measures, but is related to health and infrastructure outcomes. For example, studies conducted in London show that a substantial proportion of heat-related mortality may be associated with UHI (Simpson et al., 2024). Such findings support the treatment of UHIER as a systemic risk. Overall, the UHIER scenario provides a suitable ground for testing the applicability of the AGICore approach in the city–disaster–NbS context. The clarity of the physical mechanisms, the availability of data, and the diversity of interventions support this choice. Therefore, UHIER is addressed not only as an application area but also as a reference scenario through which the AGICore framework may be extended to different types of urban risks.

2.2. Sample and Study Design: Monitoring the Heat Island Regime in Urban Regeneration Areas

In this study, the sample was constructed through two large-scale urban regeneration areas in Ankara: the New Mamak Urban Regeneration Project (NMURP) and the North Ankara Urban Regeneration Project (NAURP). NAURP covers approximately 1,583 ha, while NMURP covers approximately 700 ha, and both areas are located in the northeastern part of the city. These characteristics make it possible for the sample both to produce a meaningful thermal signal at the city scale and to allow the differentiation of different intervention intensities within the same project boundaries (Ozenen Kavlak et al., 2025). The analytical value of the sample derives not only from covering two project areas, but also from the fact that transformation has occurred at different stages within these areas. NAURP consists of a three-stage structure, and its first stage has been completed. NMURP, by contrast, proceeds through an eleven-stage process, with redevelopment completed in some stages while transformation continues in others (Ozenen Kavlak et al., 2025). These stage differences make it possible to analyze different intensities within the same spatial framework instead of treating intervention as a single process. The temporal dimension was designed to enable comparison between pre- and post-transformation conditions. For this purpose, a Landsat-5 (TM) image dated 03.07.2005 was used to represent the pre-transformation period, while a Landsat-8 image dated 02.07.2022 was used to represent the post-transformation period (Ozenen Kavlak et al., 2025). Dates corresponding to similar seasonal and meteorological conditions were preferred in order to ensure measurement consistency.

The spatial sample universe was defined as the pixel population located within the project boundaries. LST and the derived heat island indicators were calculated over this universe. This approach makes it possible to monitor thermal change through both general trends and spatial differences. The findings indicate a weakening trend in the heat island effect at the overall level, while also showing that local increases may occur in some densely built sub-regions (Ozenen Kavlak et al., 2025). The definition of the rural reference is a critical component of the sampling design. Since UHIER indicators are calculated through the difference between urban surfaces and a rural baseline, the selection of the reference area directly affects the results. In this study, the rural reference was determined by using two 5-km buffer rings. The first ring was excluded from the analysis due to the heat island footprint effect, while in the second ring areas distant from urban influence and with high data quality were preferred. In the final stage, a reference area of approximately 5×5 km, dominated by rural classes, was defined using the CORINE land cover dataset (Ozenen Kavlak et al., 2025). Land cover transformation and morphological change were associated with CORINE Land Cover datasets (2006 and 2018). In this way, it was possible to trace within the same sample universe the land cover transitions together with which thermal change occurred. This approach focuses not only on the presence of transformation but also on its character. Although the sample was defined by project boundaries, the analytical unit was addressed as pixel compositions and stage-based sub-regions representing spatial heterogeneity.

2.3. Measurement Design, UHIER Logic, and the AGICore Traceability Core

The measurement design of this study is based on analyzing UHIER through satellite-based LST indicators rather than through meteorological station data. This preference places the analysis at the surface UHIER level rather than the atmospheric UHIER level and makes it possible to monitor the direct thermal behavior of urban surfaces (Ayala-Carrillo et al., 2022).

The analysis is based on the relative difference between LST values obtained at two time points for urban and rural areas (Ozenen Kavlak et al., 2025). The UHIER approach used to express this difference quantitatively has a methodological framework similar to that of the URI family of indicators (Xu & Chen, 2004). In this study, UHIER was defined as the relative LST difference, and interpretation was based on the magnitude and direction of this difference. Negative values indicate situations in which urban areas are cooler, whereas positive values indicate situations in which they are warmer. This approach transforms UHIER from being merely a visual mapping output into an analytical evaluation tool. The contribution of the AGICore framework, in turn, is to convert this analytical chain into a traceable and auditable structure. In the analysis, LST was calculated from Landsat data and CORINE land cover datasets, and the UHIER indicator was derived (Ozenen Kavlak et al., 2025). The resampling of the thermal band from its nominal 100 m resolution to 30 m was taken into consideration as a limitation in spatial interpretation. UHIER maps were analyzed by dividing them into five classes. In addition, change maps were produced for change analysis and the results were classified. Raster data were converted into point data, numerical analyses were carried out, and average values were calculated according to land cover classes. This procedure made it possible to present the results not only visually but also as comparable data outputs.

The AGICore approach structures this process through three main principles: traceability, reproducibility, and reusability. Data sources, processing steps, and parameters were recorded in order to ensure the transparency of the analytical process (Peng, 2011; Wilkinson et al., 2016). Within this scope, three main limitations were explicitly stated: the sensitivity of rural reference selection, classification errors in the

CORINE dataset, and the resampled resolution of the thermal data. The explicit statement of these limitations strengthens the reliability of the method.

2.4. The AGICore Inference Layer in the Context of UHI–Urban Regeneration–NbS

This study does not leave the UHIER-based analytical chain at the measurement level, but completes it with an inference layer within the AGICore framework. This framework aims to control the methodological risks that arise when moving from a single indicator to higher-level interpretations. The AGICore approach seeks to limit three main biases: the masking of spatial variation by area-wide averages, the oversimplification of mechanisms by land cover proxies, and the treatment of transformation processes as a single intervention. For this reason, the analysis is addressed across three planes. The first plane is the data and evidence plane. The analytical process is defined as a traceable and reproducible workflow. The second plane is the mechanism plane. UHIER patterns are related to the components of surface energy balance. The third plane is the intervention plane. The transformation area is treated as a structure composed of different stages. This approach places spatial variation at the center of the analysis by preventing generalized conclusions. In this way, findings are interpreted not only through average values but also through local differences. AGICore's relation to NbS is defined not by producing a new index, but by establishing a mechanism-based evaluation framework. Green area increase is not directly associated with temperature reduction; instead, it is considered together with shading, evapotranspiration, and surface properties. This approach avoids reductionist interpretations and makes it possible to evaluate different thermal patterns occurring simultaneously within the same sample (Ozenen Kavlak et al., 2025).

3. AGICore-Centered Evidence Structure and Spatial Contradiction Filtering

The purpose of this section is to reveal local counterexamples that may be obscured by area-wide averages and, in doing so, to operationalize AGICore's principle of "contradiction filtering" at the evidence level. Within this framework, cooling signals and local warming clusters emerging under the same intervention structure are evaluated together, while the levels of data, mechanism, and agency are distinguished from one another and traced separately. In this way, the findings can be interpreted not through a single average value but through spatially differentiated patterns.

For NMURP, the confinement of the UHIER range between −0.23 and 0.28 in 2005 and between −0.12 and 0.13 in 2022 appears, at first glance, to indicate a narrowing of thermal extremes at the surface (Ozenen Kavlak et al., 2025). From the AGICore perspective, however, the decisive issue is the spatial distribution of this narrowing. The increase in the low UHIER class from 100 ha (13%) to 240 ha (30%) and the decrease in the medium class from 655 ha (82%) to 511 ha (64%) show that the overall cooling signal was produced largely through a "medium → low" transition (Ozenen Kavlak et al., 2025). By contrast, the increase in the high class from 35 ha to 46 ha reveals that local thermal concentrations also intensified within the same spatial system. This result clearly shows that "overall cooling" and "core warming" can coexist simultaneously. Class transitions make this pattern even clearer. In NMURP, the largest decrease occurs in the "medium → low" transition with 166 ha, whereas the largest increase occurs in the "medium → high" transition with 41 ha. In addition, the fact that 448 ha remained unchanged as "medium → medium" indicates that the transformation effect was not distributed evenly across the area (Ozenen Kavlak et al., 2025). Although the decline of the "very high" class from 5 ha to 0 ha points to a reduction in extreme

values, the expansion of the "high" class suggests that an upward shift from within the medium class continued. This coexistence provides direct evidence that the intervention did not produce a homogeneous environmental effect. A similar but broader-scale pattern is observed in NAURP. The change in the UHIER range from −0.23 to 0.25 in 2005 and from −0.15 to 0.20 in 2022 shows that the general narrowing trend also continued here (Ozenen Kavlak et al., 2025). The increase in low UHIER areas from 268 ha (16%) to 455 ha (27%) and the decrease in high UHIER areas from 203 ha (12%) to 87 ha (5%) indicate a clear cooling signal at the area-wide level (Ozenen Kavlak et al., 2025). However, the change balance shows the coexistence of 480 ha of decrease, 184 ha of increase, and 1,027 ha of unchanged area. The largest decrease occurs in the "medium → low" transition with 261 ha, whereas the largest increase occurs in the "low → medium" transition with 111 ha (Ozenen Kavlak et al., 2025). This distribution suggests that local warming pockets in NAURP also follow a systematic spatial pattern rather than a random one. At this point, AGICore's agency plane becomes relevant. In NAURP, the observation of increase or no-change patterns especially in the first stage, the production of an overall decrease by afforested areas in the second stage, and the emergence of increases around the third stage together with new construction areas show that different types of interventions can generate different thermal regimes (Ozenen Kavlak et al., 2025). This finding clearly indicates that transformation should be treated not as a single intervention, but as the combination of stage-based sub-interventions.

Land cover classes and UHIER averages quantitatively support the mechanism plane. In NMURP, the rise of the discontinuous urban fabric class from 81% in 2006 to 91% in 2018, together with the decline of agricultural classes, shows that urban intensification increased (Ozenen Kavlak et al., 2025). In NAURP, the increase of the green urban areas class from 0 to 5%, despite simultaneous increases in the road network and urban surfaces, shows that cooling and heating effects operate together within the same system (Ozenen Kavlak et al., 2025). This clearly demonstrates the inadequacy of direct equivalences such as "green increase = cooling." Class-based average UHIER values also support this complexity. In NAURP, the observed increase in the average UHIER values of urban texture classes shows that intensification continued to produce thermal risk. By contrast, the shift of agricultural and semi-natural classes toward more negative values confirms the cooling effect of these classes (Ozenen Kavlak et al., 2025). In NMURP, although average cooling was observed in some urban classes, the more stable behavior of other classes indicates that not all surface types responded in the same direction. This finding shows that UHI cannot be explained through a single mechanism and must be evaluated in a context-sensitive way. When these findings are considered together, AGICore's evidence structure reaches the following conclusion: in both projects, UHI generally shows a decreasing trend. However, the local increases that emerge in transformation cores and in certain stages show that environmental benefit is not achieved automatically. When the intervention is not carefully designed through the composition of morphology, impermeability, and green infrastructure, UHI can be reproduced in new forms (Ozenen Kavlak et al., 2025). Therefore, the conclusion reached here should be evaluated not as a success narrative based on area-wide averages, but as an inference tested through spatial contradiction filtering.

4. AGICore-Based Inference and Transferable Lessons for City–Disaster–NbS

The main AGICore-based result of this study is that urban regeneration does not produce a unidirectional and homogeneous improvement in the heat island regime. In NMURP and NAURP, the narrowing of the UHIER spectrum and the expansion of low-class areas indicate an overall cooling signal. However, the

expansion of high-class areas in certain stages and transformation cores, or the emergence of local thermal increases through low→medium transitions, shows that some components of the intervention continue to produce thermal risk (Ozenen Kavlak et al., 2025). This finding clearly demonstrates that environmental benefit is determined not by the mere presence of the intervention, but by the morphological and surface composition produced by that intervention.

At this point, the NbS discussion is situated within AGICore's regulation plane. An increase in green space alone is not sufficient to reduce the heat island effect. In NAURP, the increase in green urban areas together with the strengthening of road network and urban texture dynamics shows that cooling and heating effects operate simultaneously (Ozenen Kavlak et al., 2025). Therefore, the effect of NbS must be evaluated together with site selection, continuity, maintenance, evapotranspiration capacity, and shading geometry. Otherwise, "green increase" remains at the level of a superficial intervention rather than becoming a mechanism that transforms the thermal regime. This indicates that environmental performance in urban regeneration projects should be monitored not through average indicators, but through stage-based measures that make spatial heterogeneity visible.

The most important contribution AGICore makes to this article is not to expand the scope of the claim, but to sharpen its limits. Instead of generalizations such as "transformation reduces UHI," a more careful formulation is proposed: transformation may reduce UHIER in some sub-regions while increasing it in certain morphological and stage combinations. For this reason, environmental benefit becomes more transferable and reliable only when gray and green components are designed together at the mechanism level. In this way, UHI is moved beyond being merely a comfort indicator and is considered one of the measurable components of urban resilience.

Although the evidence structure of the reference study is strong, it preserves its validity only insofar as its scope is clearly defined. The first limitation is that the measurement is based on LST. LST represents a physical quantity different from atmospheric UHIER and is indirectly related to human exposure (Voogt & Oke, 2003; Weng, 2004). Therefore, the study does not make a direct causal inference regarding health effects, but rather reveals surface thermal patterns. This distinction is not a weakness of the method, but a deliberate methodological limitation that prevents overgeneralization. The second limitation concerns the spatial resolution of the thermal band. The resampling of 100 m resolution to 30 m may create an illusion of detail, especially in small-scale thermal cores (Ozenen Kavlak et al., 2025). Therefore, while the analysis reliably shows the existence of thermal cores, it acknowledges that their boundaries may not be determined with high precision. The third limitation concerns the temporal mismatch and classification structure of CORINE datasets. CORINE classes are treated not as direct mechanisms but as proxy indicators supporting interpretation. Therefore, they are not expected to provide causal explanation on their own (Ozenen Kavlak et al., 2025). The fourth limitation is the heterogeneous nature of transformation. Different stages involve different intervention intensities and design characteristics, which limit precise causal differentiation. For this reason, the claim of the study is strong but limited. Different intervention combinations within the same project boundary may produce different thermal regimes.

The value of AGICore in this study derives not so much from presenting a case analysis specific to Ankara, but from proposing a transferable evidence structure. However, this transferability depends on the explicit definition of contextual differences (Pearl, 2015). For this reason, the AGICore protocol begins with two basic steps: the explicit definition of the study area and intervention sub-components, and the transparent

determination of the rural reference. These two steps are prerequisites for reconstructing the same framework in different cities. The next step is to make the data and workflow traceable. Beginning with Landsat scenes, the entire process of LST production, UHIER calculation, and classification is defined within a provenance chain (Lebo et al., 2013). This approach meets the reproducibility standard of scientific claims (Peng, 2011) and supports the shareability of workflows in line with FAIR principles (Wilkinson et al., 2016). Thus, the study not only produces results, but also offers a reproducible methodological object. The third step is the construction of a mechanism vocabulary. UHIER patterns are evaluated together with land cover proxies and, where possible, morphological classifications (Stewart & Oke, 2012). This structure makes it possible to conduct comparable mechanism analyses across different cities. The fourth step is sensitivity testing and contradiction filtering. Fragilities such as rural reference selection, dataset mismatches, and spatial resolution need to be tested systematically. This approach strengthens the reliability of the results rather than merely their magnitude.

When the study findings are evaluated, the AGICore protocol does not only produce UHIER maps, but also generates a comprehensive spatial evidence package that makes intervention heterogeneity visible. This package includes class distributions, transition matrices, difference maps, and mechanism interpretations together. In this way, the study provides a more robust basis for decision-making by showing which intervention combinations lead to which thermal outcomes, rather than offering a single-sentence success narrative. This approach also confirms AGICore's core claim. What is decisive is not the scale of the claim, but the strength of the evidence structure that supports it.

5. Conclusion

This study defines AGICore not as a single-output treatment of urban and climatic risks, but as a methodological core through which physical signals are transformed into traceable and decision-relevant evidence. This approach is deliberately bounded. AGICore does not claim to be a universal law or a comprehensive model that explains all disciplines. Rather, it proposes an epistemic architecture that ensures that each analytical step remains auditable under thermodynamic consistency, the limits of information theory, and explicit structural assumptions. In this respect, AGICore may be considered a scientific governance tool that addresses the city not only through metrics, but also as a socio-ecological-technical system.

The fact that this framework is built around UHIER is not accidental. On the contrary, it constitutes a kind of methodological stress test. UHIER is analytically demanding because it is measurable through LST, multi-causal, and produces spatial inequalities as a risk regime. The findings obtained from the transformation areas in Ankara also clearly show why interpretation must be structural. Even when UHIER values decline at the overall area level, local warming cores may still emerge in transformed and densely built sub-regions (Ozenen Kavlak et al., 2025).

The main empirical result of this study is as follows: the thermal effect of urban transformation is determined not by the name of the intervention, but by the composition of morphology, impermeability, and green infrastructure that it produces. For this reason, AGICore considers success narratives based on area-wide averages methodologically insufficient. The narrowing of the UHIER spectrum alone is not sufficient evidence of environmental improvement. What is decisive is not only where heat decreases, but also where it increases, through which land cover transitions it is carried, and under which stage

combinations it emerges. For this reason, transformation must be evaluated not as a single intervention, but as a multi-component mechanism. AGICore's contribution lies in making these contradictions visible and auditable. First, it keeps inferences from remote sensing data within physical and informational limits (Landauer, 1961; Shannon & Weaver, 1949). Second, it treats observed change not as a random fluctuation, but as a structural process, thereby enabling dynamic interpretation (Tu et al., 2013). Third, it clearly distinguishes observational relationships from policy implications and places causal claims on a more responsible basis (Pearl, 2015). Finally, it grounds scientific defensibility in the principles of reproducibility and traceability (Peng, 2011; Wilkinson et al., 2016; Lebo et al., 2013). This approach is particularly important for NbS. The literature shows that the cooling effect of greening is real, but that this effect varies according to context (Bowler et al., 2010; Ziter et al., 2019). For this reason, statements such as "green space increase reduces UHI" are not scientifically sufficient on their own. From the perspective of AGICore, the essential output is not a single temperature difference, but an evidence map capable of showing which mechanisms operate under which conditions and with which spatial outcomes.

The Ankara case also clearly reveals the limits of the method. LST represents surface temperature, not direct human exposure. CORINE datasets are not the mechanism itself, but proxies supporting interpretation. Transformation, moreover, is not a homogeneous intervention. The strength of AGICore lies not in concealing these limitations, but in explicitly defining them and determining the scope of interpretation accordingly. As a result, the value of AGICore is both methodological and institutional. On the one hand, it keeps urban climate analyses within physical and informational limits; on the other hand, it makes these analyses applicable to planning and decision-making processes. This approach demonstrates that urban regeneration interventions do not only produce improvement, but may also create new thermal inequalities at the same time. An AGICore-compatible analysis makes these simultaneous effects visible, testable, and reproducible. For this reason, AGICore should be understood not as a universal theory, but as a verifiable methodological framework that disciplines the process of evidence production for cities that must make decisions under high uncertainty.

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been developed and implemented using the Python programming language, supporting transparent data processing, reproducible analysis pipelines, and extensible methodological integration.

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