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Modelling Nature Connectedness Within Environmental Systems: Human-Nature Relationships from 1800 to 2020 and Beyond

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Abstract

Amid global environmental changes, urbanisation erodes nature connectedness, an important driver of pro-environmental behaviours and human well-being, exacerbating human-made risks like biodiversity loss and climate change. This study introduces a novel hybrid agent-based model (ABM), calibrated with historical urbanisation data, to explore how urbanisation, opportunity and orientation to engage with nature, and intergenerational transmission have shaped nature connectedness over time. The model simulates historical trends (1800–2020) against target data, with projections extending to 2125. The ABM revealed a significant nature connectedness decline with excellent fit to the target data, derived from nature word use in cultural products. Although a lifetime 'extinction of experience' mechanism refined the fit, intergenerational transmission emerged as the dominant driver—supporting a socio-ecological tipping point in human–nature disconnection. Even with transformative interventions like dramatic urban greening and enhanced nature engagement, projections suggest a persistent disconnection from nature through to 2050, highlighting locked-in risks to environmental stewardship. After 2050, the most transformative interventions trigger a self-sustaining recovery, highlighting the need for sustained, systemic policies that embed nature connectedness into urban planning and education.

Keywords: nature connectedness; extinction of experience; agent-based model; urbanization; intergenerational transmission; socio-ecological systems; cultural indicators; environmental psychology; transformative change

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1. Introduction

Global environmental changes, driven by urbanisation and land-use shifts, have reduced opportunities for individuals to experience nature and diminished their orientation toward the natural world. This has resulted in a disconnection from nature, particularly in the Western world, that is now recognised by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as a causal factor in the environmental crises of biodiversity loss and climate change [1]. The IPBES Transformative Change Assessment sees nature connectedness as a powerful strategy for the transformative change needed for achieving the 2050 Vision for Biodiversity [1]. The reduction in exposure to nature (opportunity) and the decreasing affinity for it (orientation), which together create a cycle that weakens the human-nature relationship, is referred to as 'extinction of experience' [2,3]. Human–environment interactions, or the human-nature relationship, are increasingly considered through the psychological construct of nature connectedness, which is critical for fostering pro-environmental behaviours and enhancing human wellbeing [4,5]. Yet, historical processes like urbanisation and environmental degradation have likely driven its long-term decline, with few longitudinal studies exploring these dynamics [6].

This study helps address this research gap by employing an agent-based model (ABM) to investigate these interactions over 220 years and into the future, offering insights into how urbanisation, opportunity, orientation, population dynamics and intergenerational transmission have combined to shape the historical trajectory of nature connectedness. These insights can inform initiatives in areas such as urban planning and conservation strategies that aim to restore the human-nature relationship.

While access to greenspaces (opportunity) is a growing policy focus, orientation toward nature is an equally significant factor [7,8]. The personal affinity with nature captured by orientation, forms an essential feature captured by the nature connectedness construct. Thereby driving behaviour and delivering broader benefits for both human and nature's wellbeing [4,5]. Furthermore, active sensory engagement with nature fosters nature connectedness more effectively than passive exposure [9], with eye-tracking studies showing that higher nature connectedness correlates with greater visual attention to natural elements (e.g., trees) over built environments [10]. These findings highlight the need to understand how opportunity and orientation, modulated by urbanisation, shape nature connectedness over time.

A 2025 study by Kamphuisen et al. explored the relationship between nature availability, nature experiences and nature connectedness in recent research that formally tested the dynamic properties of extinction of experience using an ABM [11]. Kamphuisen et al. demonstrated how nature availability, nature experiences, and nature connectedness interact within greenspace scenarios. They explored how varying levels of greenspace availability influence system behaviour and found evidence of tipping points where small reductions in greenspace trigger disproportionate shifts in system behaviour. While Kamphuisen et al. provide a robust simulation of the extinction of experience's feedback loops and short-term cycles to explore tipping point dynamics, it does not aim to explore parental influence or the historical evolution of nature connectedness across centuries. As such it does not incorporate population dynamics or intergenerational transmission, factors that are essential for understanding the long-term decline and recovery of nature connectedness across generations.

There is limited research on intergenerational transmission of nature connectedness, however there are pointers towards genetic and familial influences. Twin studies indicate moderate heritability of nature orientation (46%), suggesting genetic contributions [12]. Parental nature connectedness has also been found to be the strongest predictor of child nature connectedness, amplifying or mitigating decline in urban settings [13]. Low parental orientation may perpetuate the extinction of experience cycle, particularly where nature access is limited. These findings underscore the importance of considering not only individual experiences with nature across the lifespan but also the familial pathways through which nature connectedness is passed down to children. Longitudinal models capturing these dynamics are critical to inform interventions that strengthen nature connection and support nature conservation. The ABM used in the present research incorporates intergenerational transmission, historical urbanisation data and orientation to attend to nature and enables the exploration of population dynamics over time, including how demographic shifts and family structures influence nature connectedness across generations.

Intergenerational transmission introduces a form of systemic inertia into the human–nature relationship, making it a critical mechanism for understanding long-term trends. Even if environmental conditions improve—such as increased access to green spaces or urban greening initiatives—the benefits may not be immediately realised if previous generations have passed on low levels of nature orientation. This creates a lag effect, where the psychological and behavioural disconnection from nature persists across generations, delaying recovery and reinforcing the extinction of experience. Nature connectedness is not solely shaped by individual encounters with the environment; it is also deeply embedded in familial norms, social learning, and cultural practices [1]. When these pathways are disrupted, by urbanisation for example, the disconnection can become self-reinforcing. This positions intergenerational transmission not as a peripheral factor, but as a structural driver of long-term disconnection from nature. Including it in the ABM is therefore essential, as it allows for the simulation of how inherited dispositions interact with changing environmental opportunities, revealing the compounding effects that shape population-level patterns of nature connectedness over time.

Exploring the evolution of nature connectedness over time requires data driven calibration and validation against cultural trends. This historical scope is essential for understanding global environmental changes and human-made risks. This study extends the extinction of experience approach by modelling its historical context, providing a complementary perspective to Kamphuisen et al.'s work and enhancing our understanding of human-nature relationships across a 220-year span and several generations into the future. Finally, this approach fits the resilience perspective, providing a further theoretical foundation through framing the human nature relationship as a social–ecological system characterised by non-linear dynamics, thresholds, and feedbacks across temporal and spatial scales [14].

1.1. Agent Based Models

ABMs are computational tools well-suited to simulating the complex, dynamic interactions, such as the extinction of experience cycle [11]. ABMs model individual agents (representing people) with internal states (e.g., nature connectedness) and behaviours (e.g., noticing nature) that evolve through interactions with their environment (e.g., urban or natural settings) and other agents (e.g., parents and children). Crucially, ABMs are uniquely capable of representing heterogeneous populations—agents can differ in age, nature connectedness levels, and responsiveness to environmental cues—allowing for a more realistic simulation of how diverse individuals interact over time. Unlike cross-sectional studies using approaches such as linear regression that identify associations, ABMs capture emergent system-level patterns [15], and can uncover the causal mechanisms in the decline of nature connectedness, from individual-level rules, making them ideal for testing theoretical assumptions about opportunity, orientation, and transmission when empirical data is limited or incomplete [16].

By simulating nature connectedness dynamics from 1800 to 2020, the ABM integrates historical levels of urbanisation (from 7.3% to 82.7%) [17], opportunity (grid-based nature availability), orientation (agent nature connectedness and attention to nature), and intergenerational transmission. The model directly simulates how parental nature connectedness influences that of their children, allowing disconnection to propagate across generations. This highlights the critical role of familial influence as a dynamic, generational process—something a static regression model cannot capture. In addition, the ABM tests how local environmental conditions (e.g., proximity to nature versus urban areas) shape individual nature connectedness over time. It shows how urbanisation, by reducing nature availability, not only affects individuals' ongoing experiences but also lowers the initial connectedness of new generations, creating complex feedback loops. A key strength of the ABM lies in its ability to track individuals across their lifespans, model population dynamics, and test "what-if" scenarios. This includes projections under transformative interventions, such as urban greening or increased societal attention to nature. As such, the ABM provides a superior, process-based understanding of how and why urbanisation and intergenerational dynamics have driven the historical decline in nature connectedness.

Similar to Kamphuisen et al., the ABM approach detailed below employs core extinction of experience components, namely nature availability, nature experiences and nature connectedness [11]. In the 'lifetime' feedback loop greater local nature availability drives opportunities for engagement, which strengthens, or weakens, nature connectedness in an individual through dynamic attention to natural elements. An 'intergenerational' feedback loop captures environmental and intergenerational transmission, where parental nature connectedness and local nature shape child nature connectedness, amplifying the extinction of experience cycle in urbanising environments with declining nature availability. These two loops reflect the within and across lifetime pathways suggested by Soga and Gaston [3], and capture non-linear socio-ecological dynamics, driven by urbanisation and environmental degradation. Because ABMs allow for these feedbacks to emerge from the bottom up—rather than being pre-programmed—they are particularly well-suited to exploring how small changes in individual behaviour or environmental context can lead to large-scale shifts in system behaviour.

1.2. Research Questions

The extinction of experience framework suggests that urbanisation and environmental degradation reduce nature availability, limiting experiences that foster nature connectedness [2,3]. Therefore, historical processes, such as the Industrial Revolution, likely drove long-term nature connectedness decline. However, longitudinal studies are scarce, creating a gap in the available research. Further, the validity of ABMs depends on replicating historical trends. However, long-term empirical data is limited. To address this, the frequency of nature engagement words in cultural products (e.g., books) was used as a proxy for historical nature connectedness [18]. This leads to RQ1: Can an agent-based model replicate the evolution of nature connectedness from 1800 to 2020 in response to urbanisation and environmental degradation?

In addition to lifetime extinction of experience drivers, intergenerational transmission is likely to play a significant role over time. Therefore, RQ2 is: What role does intergenerational transmission play in sustaining or amplifying the decline in nature connectedness over time?

Finally, projecting future trajectories is critical to understanding the long-term implications of current trends and approaches to interventions such as urban greening initiatives and increased societal attention to nature, especially given the possibility of tipping points [11]. This leads to RQ3: What is the projected trajectory of nature connectedness by 2125 under scenarios of urban greening, increased attention to nature, and enhanced intergenerational transmission?

The ABM and these questions capture core interactions between humans and natural systems. These dynamics are critical, as declining nature connectedness has contributed to and exacerbated environmental crises, with implications for human health. This study addresses the pressing need to understand the trajectory of nature connectedness amid global environmental changes, driven by urbanisation and environmental degradation.

2. Materials and Methods

2.1. Conceptual Framework

The hybrid data-driven ABM simulates the long-term evolution of urban expansion, nature degradation, and family dynamics, capturing interactions between individuals, families, and their environment over time. The framework integrates macro-scale historical data with micro-scale decision-making processes, linking human-nature relationships to environmental change and societal factors. It is grounded in the extinction of experience framework, which posits a vicious cycle where declining nature availability reduces nature experiences, eroding nature connectedness [2,3]. This framework is extended to simulate nature connectedness dynamics from 1800 to 2020, capturing historical urbanisation and environmental degradation. The model's system map (Figure 1) summarises the model's structure and the dynamic and recursive nature of the model. It provides a general overview of the model's core components and their interactions. It comprises nature and agents, and two feedback loops between them: (1) an annual lifetime loop where local nature availability drives nature connectedness through dynamic attention to natural elements, which is in turn driven by nature connectedness; and (2) an intergenerational loop where parental nature connectedness and local nature combine to set child nature connectedness at birth.

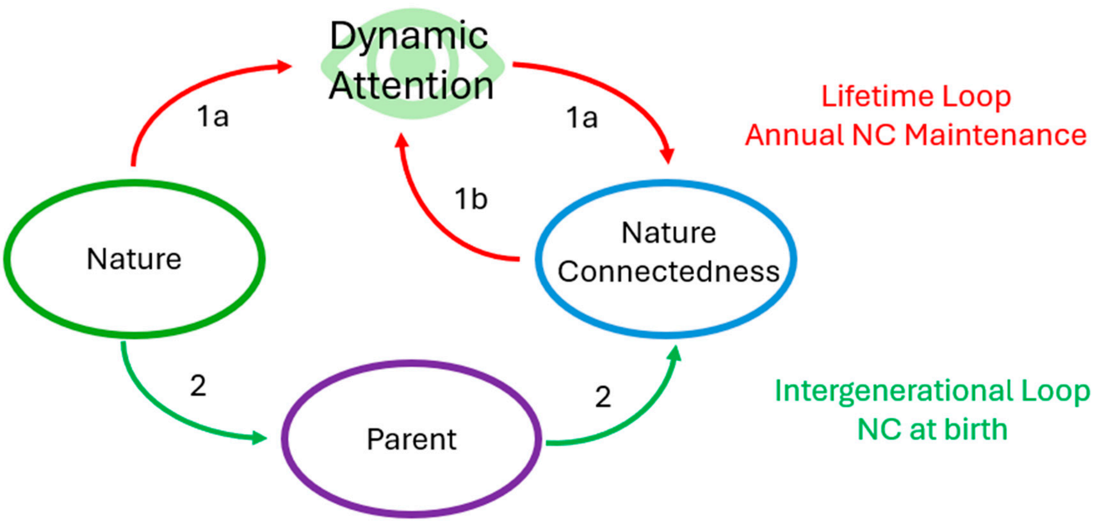

Figure 1. The ABM's conceptual framework, illustrating entities (environment, agents, families) and feedback loops.

2.2. Modelling Approach

The model employs a grid-based spatial representation where cells correspond to environmental states: nature, urban, or degraded (to reflect post 1970 biodiversity loss). Families occupy urban cells and evolve through individual life cycles, reproduction, and migration. Environmental transitions occur as urban areas expand and nature degrades, with nature connectedness values influencing agents' attention to natural surroundings.

Implemented in Python, 3.1.1 the ABM represents individuals as agents within families, interacting with a grid-based environment from 1800 to 2020. Figure 2 shows a snapshot illustration of the grid-based environment at two years in the simulation, showing how urban areas (red) increased and natural areas (green) declined. The blue cells represent the generations of families living within this environment which provides decreasing access to local nature.

This hybrid ABM integrates data-driven inputs (urbanisation) with theoretical mechanisms (noticing, saturation, intergenerational transmission), capturing complex nature connectedness dynamics. Grid search ensures robustness by tuning parameters to align simulated nature connectedness with historical cultural trends in nature-related language use. Given the greater Western disconnection from nature and US bias in the English language corpus used to model cultural trends in nature connectedness, a fixed, time dependent parameter, integrates historical US urbanisation data [17] to drive transitions from nature to urban cells, reflecting urban expansion from 7.3% in 1810 to 82.7% in 2020.

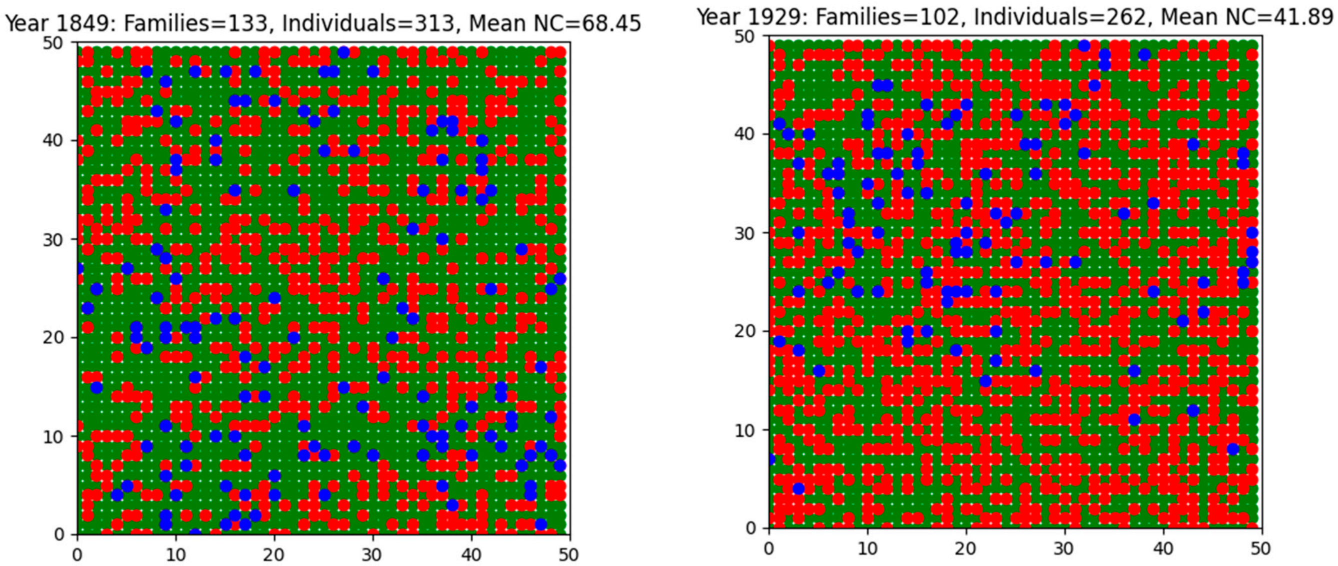

Figure 2. Snapshot illustration of grid-based environment with nature, urban and family cells in 1849 and 1929 (Red = urban areas; green = natural areas; blue = families).

2.3. Model Entities and State Variables

The ABM includes three primary entities: environment, agents and families (See Figure 3).

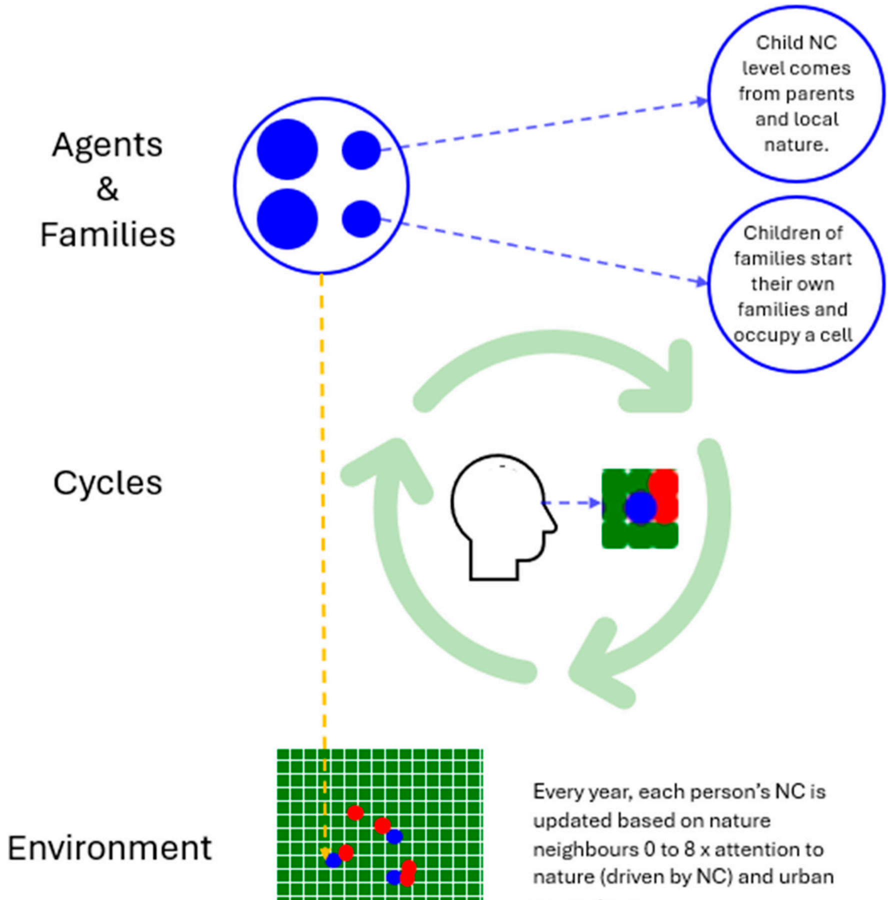

Figure 3. Intergenerational transmission and local nature shapes child nature connectedness.

2.3.1. Environment

The environment is a 40 × 40 grid (1600 cells), with each cell representing an abstract spatial unit (not tied to a specific geographic scale, chosen for computational efficiency). At initialisation, 7.3% random cells are urban, with 100 cells occupied by families, leaving approximately 87% of the grid as nature—reflecting pre-industrial conditions. Urbanisation progresses annually by interpolating historical data from a macro table (e.g., urban percent increases from 7.3% to 82.7%). New urban cells are allocated randomly from all available nature cells across the entire grid. As nature loss is tied to urbanisation, an independent degradation process converts nature cells to degraded cells from 1970 to avoid nature loss simply mirroring the plateauing of urbanisation and thereby simulate environmental decline data for the region [19].

2.3.2. Agents (Individuals and Parents)

Agents represent individuals grouped into families, each occupying a single grid cell. The simulation initialises with 100 families in 1800. Each agent has attributes: age, lifespan (mean: 65 years, variation: ±10), nature connectedness (initial mean: 69, standard deviation: 5 on a 0–100 scale), nature connectedness at birth, and dynamic attention (a parameter reflecting responsiveness to nature exposure). Families are placed randomly on non-urban cells at initialisation, with new families forming in urban cells within a 5-cell radius as the simulation progresses. Agent behaviours include aging, reproducing (at ages 18–25), forming new families, and updating nature connectedness based on local nature availability.

2.3.3. Cycles and Agent-Environment Interactions

The model operates in annual cycles from 1800 to 2020, with each cycle representing one year. Five key mechanisms drive the simulation, reflecting agent behaviours and environmental dynamics:

1. Urban Growth: Urban cells expand to match the target urban percent by converting nature cells to urban cells if the current urban proportion is below the target, simulating historical urbanisation trends.
2. Nature Degradation: From 1970, a proportion of nature cells transitions to degraded cells based on available data for biodiversity loss as urbanisation starts to plateau.
3. Agent Life Cycle: Agents age by one year. Parents give birth at randomly assigned ages (18–25), producing up to two children per family. Children reaching 18 become adults, forming new families in available urban cells within a radius of their origin, reflecting urban migration.
4. Nature Connectedness Update: Each agent's nature connectedness is updated annually based on their current attention to nature, the number of surrounding nature cells (measured using a Moore neighbourhood), and a saturation constant that moderates the effect of abundant nature. The lifetime extinction of experience formula includes a threshold parameter that shifts the point at which nature exposure leads to gains or losses in connectedness [2,3]. Specifically, individuals gain nature connectedness when the weighted influence of nearby nature and attention exceeds this threshold, and lose it when it falls below. Rather than modelling time in nature, the ABM conceptualises nature experience as dynamic attention to nature or noticing, emphasising active engagement, which has been shown to explain nature connectedness more effectively than time alone [9]. Eye-tracking studies also reveal differences in attention to nature based on levels of nature connectedness [10]. Furthermore, empirical studies show that nature connectedness can increase with greater attention, even when time spent in nature remains constant [20]. Therefore, the attention variable is derived from the

agent's current level of nature connectedness, and updated nature connectedness is clipped between 0 and 100. This mechanism drives a dynamic feedback loop over the agent's lifetime, with the saturation factor controlling the intensity of environmental feedback and the scaling constant moderating the change. The saturation mechanism (or environmental feedback intensity) ensures diminishing returns, such that even nature-rich settings do not result in runaway increases in nature connectedness. This reflects research that has found that individuals with higher nature connectedness benefit less from increased attention to nature [21]. The formula for the change in nature connectedness is:

$$\Delta\text{NC} = \frac{\left(\textit{Nearby Nature} \times \textit{Attention} \times \left(\frac{1}{1 + \textit{Saturation} \times \frac{\textit{Nearby Nature}}{8}} \right) \right) - \text{Threshold}}{\text{NC Scaling Constant}}$$

5. Intergenerational Transmission: Children inherit nature connectedness through a weighted combination of parental nature connectedness [13] and environmental influence moderated by parental nature connectedness [22], adjusted based on local nature availability. The value of parent weighting thereby dictates environmental weighting. A child's initial nature connectedness is calculated as a weighted sum of their parents' average nature connectedness and the proportion of nature cells in their immediate neighbourhood. These components are moderated by parameters representing parental and environmental influence, respectively. The ChildNC Constant allows for fine-tuning, as the nearby nature count is inherently coarse. This formulation captures both hereditary and early environmental influences, with parental influence amplified by the local environment [22], representing a multiplicative interaction between social learning and environmental opportunity. The formula is:

$$\text{NCchild} = \text{Parents NC} \times \left(\text{Parent Weighting} + \frac{\text{Nearby Nature}}{8} \times \text{Environment Weight} \right) + \text{ChildNC Constant}$$

2.3.4. Parameters

Tuned and fixed parameters governing the model are listed in Table 1. The ranges of the tuned parameters were primarily selected to sufficiently cover a solution space that allowed for robust calibration against historical trends and for exploration of the system's behavior around optimal values. This tuning is a standard and necessary practice for validating ABMs against real-world data [23], especially when dealing with complex socio-ecological systems where precise theoretical priors for all parameters may not exist. These ranges were defined and optimised by the exploratory grid searches while targeting reduced Root Mean Square Error (RMSE) to the nature connectedness target.

Table 1. Summary of Variables in the ABM.

Variable Name	**Role in Model**	**Type**	**Range or Description**
START_YEAR	Simulation start year	Fixed	1800
INITIAL_FAMILIES	Starting number of families	Fixed	Typically 100; tested 50–150
INITIAL_NC_MEAN	Initial mean nature connectedness	Fixed	69
INITIAL_NC_STD	Initial standard deviation of NC	Fixed	5
LIFESPAN_MEAN	Mean lifespan of agents	Fixed	65
LIFESPAN_VARIATION	Variation in lifespan	Fixed	±10
GRID_ROWS / GRID_COLS	Grid dimensions	Fixed	40 × 40

Table 1. *Cont.*

Variable Name	Role in Model	Type	Range or Description
URBAN_PERCENT	Drives annual urban expansion	Fixed (Time-Dependent)	Varies from 7.3% to 82.7% using historical urbanisation data
CHILD_BIRTH_AGE_MIN/MAX	Age range for childbirth	Fixed	18–25
NATURE_LOSS_RATE	Post 1970 rate of nature-to-degraded conversion	Fixed	0.0026
Saturation	Environmental feedback intensity	Tuned	1–40
Parent Weighting	Weight of parental NC in child NC	Tuned	0.5–0.9
Child NC Constant	Fine-tuning environmental input to child NC	Tuned	0–5
NC Scaling Constant	Scaling constant for NC update	Tuned	1–30
NC Loss Threshold	Threshold of nearby nature cells for NC change	Tuned	0–8
Nature Connectedness	Agent's internal state	Derived	0–100
Attention to Nature	Modulates NC update	Derived	Dynamic
Nearby Nature	Nature cells in Moore neighborhood	Derived	0–8

2.4. Simulation Experiments

Simulations were conducted using a grid search across all parameter combinations, with each configuration evaluated to minimise RMSE between simulated nature connectedness and the nature connectedness target described below. Each simulation ran from 1800 to 2020, collecting annual data on mean nature connectedness, nature connectedness changes, and percentages of nature, urban, and degraded cells. The model tracked performance metrics (RMSE) and visualised results using time-series plots of nature connectedness, environmental states, and the nature connectedness target.

The model's core mechanisms include intergenerational transmission of nature connectedness and the influence of environmental exposure within the lifetime. For further insight related to RQ2, two distinct model configurations were comparatively assessed. The primary configuration incorporated the extinction of experience mechanism whereby an individual's nature connectedness could change during their lifetime based on nature access and orientation to attend to it. A second, simplified configuration removed this explicit extinction of experience mechanism, allowing individual nature connectedness to be influenced solely by the environmental conditions at birth and parental transmission.

2.5. Nature Connectedness Target

To calibrate and validate the model, a nature connectedness target was derived from word frequency data as a proxy for historical nature connectedness trends [18]. Linguistic patterns in English-language corpora reflect cultural priorities and lived experiences, such that rising urban populations are associated with changes in language use [24], with nature-related vocabulary linked to nature connectedness [25,26].

A metric for nature connectedness over time was created from word frequency data for twenty-eight elemental and descriptive nature words. These words are broad and adaptable, designed to encapsulate qualitative experiences of the natural world. They included archetypal natural elements (e.g., river) and terms that evoke sensory or visual aspects of the natural world by describing states, characteristics, or components (i.e., copse, leaves, bud, dew, mosses, mountain, heath, meadow, nature, moor, lake, river, marsh, blossom, birds, trees, coast, hills, bark, branches, twig, beak, shore, flower, bough, stamen, stream, beck), lending them a universal and enduring resonance.

This approach is in contrast to using species names [18], which may introduce variability from ecological or knowledge-based factors. Knowledge is recognised as a weak predictor of nature connectedness [27]. Species names tend to be more technical or impersonal, focusing on identification rather than experiential connection. They are also more susceptible to reflecting wildlife population trends or being influenced by factors like the proliferation of identification guides.

Word frequency data for the nature words was retrieved from Google Ngram Viewer (1800–2019). Despite some limitations, Google Ngram is a valuable tool for identifying long-term linguistic trends [28]. The sheer size of the corpus scale outweighs noise and smooths out anomalies for big-picture trends. Further, few corpuses provide continuous dataset over two centuries and it is important to gain insights into temporal trends of nature connectedness. Although able to offer unprecedented insights into culture over time, the limitations of Google Ngram data were considered and guidelines for improving the reliability followed [29,30].

To ensure content validity, word clusters, correlation analysis [28], and factor analysis were employed. Reliability was assessed by cross-referencing with another corpus, revealing that the standardised frequencies of the factor word clusters correlated strongly (r = 0.964) with frequencies from the 1.6-billion-word Hansard corpus, spanning 1803–2005, supporting the robustness of the approach across corpora. To address frequency disparities, standardisation was applied to integrate data effectively. Ratios for the nature target were calculated by aggregating the standardised ratios of all words within each category. Five-year mean standardised ratios were used to smooth out variations, ensuring stable temporal trends [29].

2.6. Sensitivity Analysis

One factor at a time (OFAT) analysis was used to isolate the effect of each parameter on model outputs and uncover the mechanisms and patterns produced by the ABM [31]. It requires theoretically relevant, impactful and interpretable parameters tied to the model's focus. Saturation and parent weighting were tested due to their theoretical relevance, along with the number of initial families, which influences environmental dynamics. The two constants used for scaling and fine-tuning were not included due to their calibration roles and limited theoretical relevance. The selected parameters below were tested around the optimum values identified by the grid search. The use of 2000 replicates per parameter value (38,000 OFAT iterations) reflects a conservative approach to sensitivity analysis, exceeding typical thresholds for ensuring statistical robustness [31]:

- Saturation: Governs the diminishing returns of nature exposure on nature connectedness growth (12, 16, 20, 24, 28).
- Parent Weighting: Determines the strength of parental nature connectedness influence in child nature connectedness calculations (0.5, 0.6, 0.7, 0.8, 0.9).
- Initial Families: Number of starting families influences environmental dynamics (50, 75, 100, 125, 150).
- Nature Connectedness Loss Threshold: Determines the number of nearby nature cells below which nature connectedness declines, representing a 'negative extinction of experience' effect (0.0, 1.0, 3.0, 6.0).

The sensitivity of the model to these parameters was assessed based on RMSE between modelled and target nature connectedness values, and the overall percentage decline in nature connectedness.

2.7. Future Scenario

To explore potential pathways for reversing the decline in nature connectedness, future scenarios extending to 2125 were developed. The future scenarios branched from the 2020 state, ensuring consistent initial conditions across all parameter combinations. Urban growth followed historical trends until 2020, after which it stabilised at 89.2% by 2050. The simulation ran until 2125 to assess long-term trends, with interventions capped at 2050 levels to evaluate self-sustaining dynamics. A grid search tested three combinations of nature influence and attention multipliers. These changes formed three interventions:

- Child nature connectedness: This intervention targeted the intergenerational transfer of nature connectedness. It directly modified the nature connectedness value of a child by 30%, for example, through school-based and parental engagement programmes. A sustained 30% increase reflects a stretch target from current interventions that often deliver 10% improvements with long-term effects untested [32]. It was introduced over 10 years with linear increases until its full effect, after which its level was maintained.
- Nature/access increase: This intervention simulated efforts to increase the amount of, or access to, nature within the environment. In the model, this translates to enhancing the nature in an individual's surroundings, thereby influencing their nature connectedness.
- Orientation/attention to nature: This represents a change in how individuals are oriented towards and engage with nature. It directly scaled an individual's attention to natural elements. A higher multiplier signifies an increased tendency for individuals to notice, appreciate, and interact with nature, which in turn influences how their nature connectedness updates.

Changes to opportunity to access nature and attention to nature were applied as a linear scaling factor starting from their 2020 baseline until 2050. These increases were delivered incrementally until 2050 and then held constant through 2125

3. Results

3.1. RQ1: Can an Agent-Based Model Replicate the Evolution of Nature Connectedness from 1800 to 2020

The ABM, incorporating extinction of experience and intergenerational transmission mechanisms, successfully simulated a decline in nature connectedness driven by urbanisation and environmental degradation. Figure 4 shows modelled mean nature connectedness (blue line) decreasing steadily as urbanisation increased (grey line) and nature availability reduced (green line) to match post-1970 degradation [19].

The primary calibrated ABM configuration, which included the lifetime extinction of experience mechanism, accurately replicated the target nature connectedness trend, achieving a mean RMSE of 0.0440 between modelled nature connectedness and the target values (black dashed line, Figure 4). To assess the robustness of the RMSE, the model was run 500 times using the optimal parameter configuration. The resulting RMSEs had a mean of 0.0440 (SD = 0.0009), with a coefficient of variation of 2.08% and a 95% confidence interval of (0.0440, 0.0441). These results confirm that the model output is statistically stable and that the reported RMSE is not the result of stochastic variation.

The grid search of parameter combinations identified optimal parameters of: Child NC Constant = 0.08, NC Scaling Constant = 21, Saturation = 20, Parent Weighting = (0.80, 0.20), NC Loss Threshold = 1. The low RMSE confirms the model's ability to align with linguistic proxies for nature connectedness. Urbanisation (7.3% in 1810 to 82.7% in 2020) and nature decline (38.39% from 1970 to 2020) matched historical data, validating the model's environmental dynamics. The saturation factor effectively limited nature connectedness growth in nature-rich settings of the early 1800s, reflecting diminishing returns. With the lifetime extinction of experience formula flipping from a positive impact on nature to nature connectedness, to negative in 1975 (Red and Orange Delta NC lines in Figure 4). Overall, the modelled decline in nature connectedness (61.5%) slightly overshot the target trend, which peaked at a 60.58% decline in 1990, and did not capture the observed uptick to 52.39% by 2020.

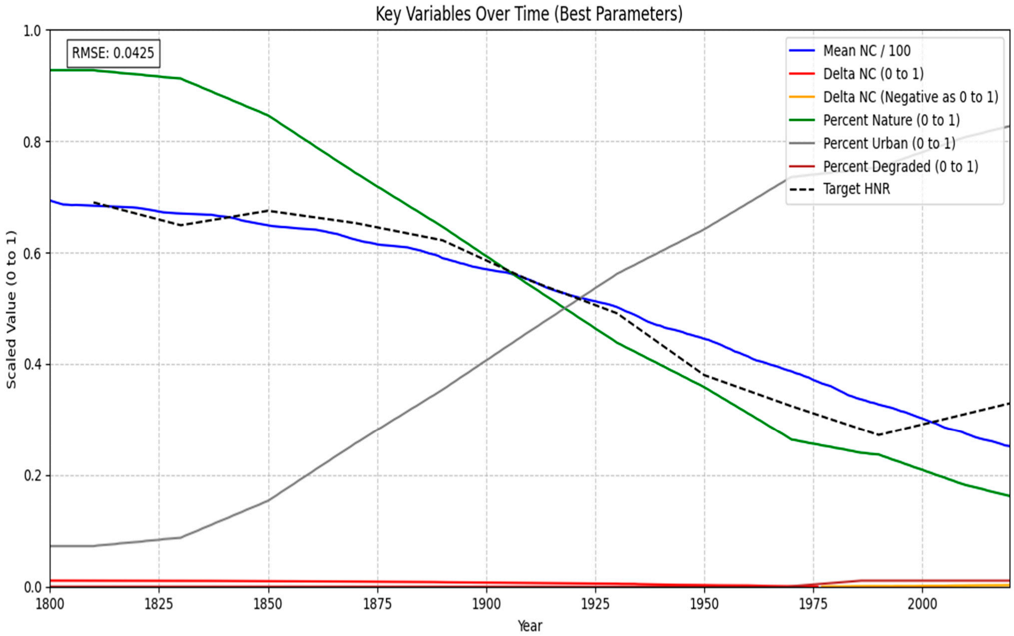

Figure 4. Time-series plot of modelled nature connectedness (blue line), environmental states (grey and green lines), and the nature connectedness target (dashed line).

3.2. RQ2: Role of Intergenerational Transmission

Intergenerational transmission was most effectively modelled using a parent weighting of 0.80 and an environmental influence weighting of 0.20. Therefore, parental influence played a significant role in sustaining nature connectedness decline. Lower parental nature connectedness in urbanising environments reduced child nature connectedness, amplifying the intergenerational extinction of experience cycle, where reduced parental connection leads to lower child nature connectedness. The importance of intergenerational transmission was highlighted by the simplified model configuration, where the annual lifetime extinction of experience loop was entirely removed. This version also yielded a strong fit to the historical data, achieving a mean RMSE of 0.0459 (SD = 0.0017), with a coefficient of variation of 3.66% and a 95% confidence interval of [0.0455, 0.0464]. with Child NC Constant = 0.18 and parental, environment weighing (0.75, 0.25). The minimal RMSE difference (0.0019) between configurations suggests that intergenerational transmission is the primary driver of long-term decline. The annual extinction of experience function refines the fit by a small amount (e.g., circa 1%), suggesting its role is secondary to the foundational influence of familial transmission on initial nature connectedness.

3.3. Sensitivity Analysis

To assess the robustness of the Agent-Based Model and identify key drivers of nature connectedness dynamics, a One-Factor-at-a-Time (OFAT) sensitivity analysis was conducted. The analysis evaluated the impact of three parameters on model accuracy and nature connectedness decline, complementing the main results by testing the model's sensitivity to parameter variations. Outputs included RMSE relative to historical nature connectedness trends and percentage nature connectedness decline (1800–2020). Results were aggregated as means and standard deviations across replicates, see Figure 5.

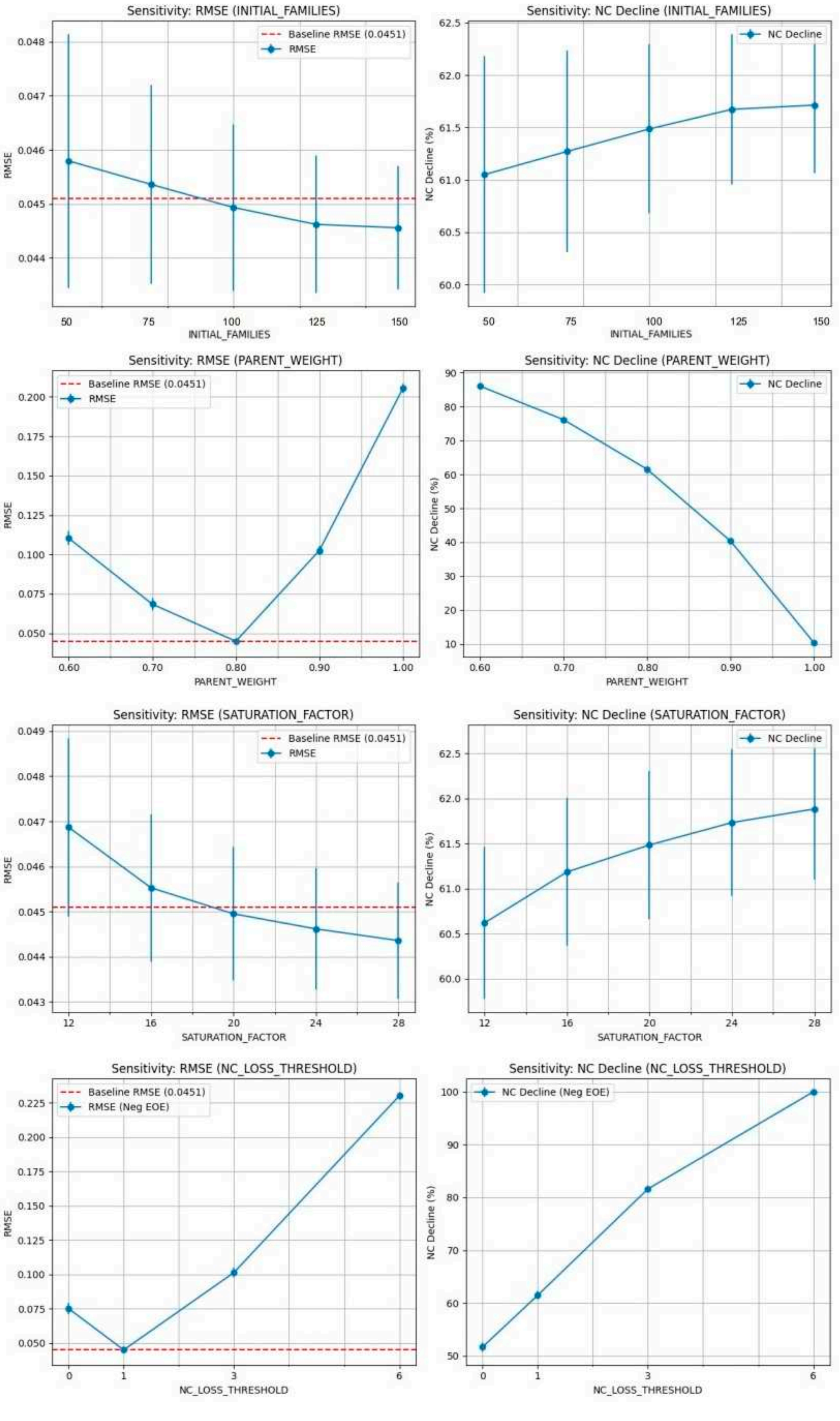

Figure 5. Sensitivity plots of RMSE and nature connectedness decline (1970–2020) vs. parameter values, with error bars indicating standard deviations across replications.

The sensitivity analysis provides valuable insights into how different parameters influence the model's performance and the resulting nature connectedness decline.

The NC loss threshold exhibited a clear and significant influence on the model (RQ1), significantly affecting nature connectedness decline and model accuracy. Specifically, higher values for this threshold resulted in a greater percentage of nature connectedness decline, but a worse model fit, indicated by a higher RMSE. A threshold value of 1.0 yielded the best fit (lowest RMSE), aligning with the optimal value found during the main grid search.

Regarding the saturation factor (Environmental Feedback Intensity), the sensitivity analysis indicated that variations across the tested range had a negligible impact on both the model's RMSE and the calculated nature connectedness decline. This suggests the model's behavior is robust to changes in this specific parameter within the values examined.

Parent weight strongly influenced both nature connectedness decline (RQ2) and model accuracy (RQ1). A parent weight of 0.80 consistently yielded the best fit (lowest RMSE), aligning with the optimal value found during the main grid search. Furthermore, the analysis showed a direct relationship between parent weight and nature connectedness decline: higher parent weight values were associated with progressively less severe declines in nature connectedness, demonstrating its crucial role in sustaining intergenerational transmission.

Finally, the initial families parameter had a minimal effect on the model's overall fit and the extent of nature connectedness decline. Across the range of initial family counts tested, the RMSE and percentage of nature connectedness decline remained largely consistent, suggesting that the initial number of families does not substantially alter the long-term dynamics.

3.4. RQ3: Projected Trajectory of Nature Connectedness

Through iterative testing, various levels of nature influence were selected to reflect varying degrees of nature restoration, intergenerational transmission and engagement with natural environments. A selection of illustrative scenarios were chosen. In the context of a tenfold increase in urbanisation since 1800, the nature access changes for the three scenarios were improvements of: 50%, 100%, and 1000% by 2050. In the context of a threefold reduction in nature connectedness since 1800 the attention to nature changes for the three scenarios were: 50%, 200% and 300% by 2050. Finally, intergenerational transmission was targeted by increasing child nature connectedness by 30%, simulating interventions such as parental engagement or school-based programmes.

The simulation results revealed three distinct clusters of trajectories, shaped by varying intervention strategies. An illustrative sample of these is presented in Figure 6.

In the first cluster—continued decline—scenarios involving increases in attention to nature or lower-level increases in nature access (50% and 100%) show mean nature connectedness continuing its historical downward trend (green and blue lines). These interventions, whether implemented alone or in combination, are insufficient to reverse the decline.

The second cluster—holding steady—includes scenarios where the decline is halted but not reversed. This includes the child-focused intervention on its own (yellow) and in combination with the lowest levels of nature access and attention interventions. This cluster includes the transformational 1000% increase in nature access alone (orange) and together with a 300% increase in attention to nature (purple).

The third and most promising cluster—transformative change—emerges when a 1000% increase in nature access is implemented together with the child-focused intervention (red), representing a combined strategy of environmental restoration and strengthened intergenerational transmission. The powerful synergistic effects of widespread nature availability and robust cultural transmission across generations, leading to a substantial and self-sustaining increase. The addition of the 300% increase in attention to nature leads to a further modest improvement. This illustrates that in a context where intergenerational transmission dominates the lifetime extinction of experience mechanism, increased attention to nature, while good for individual connectedness and wellbeing, makes little difference to changes over time.

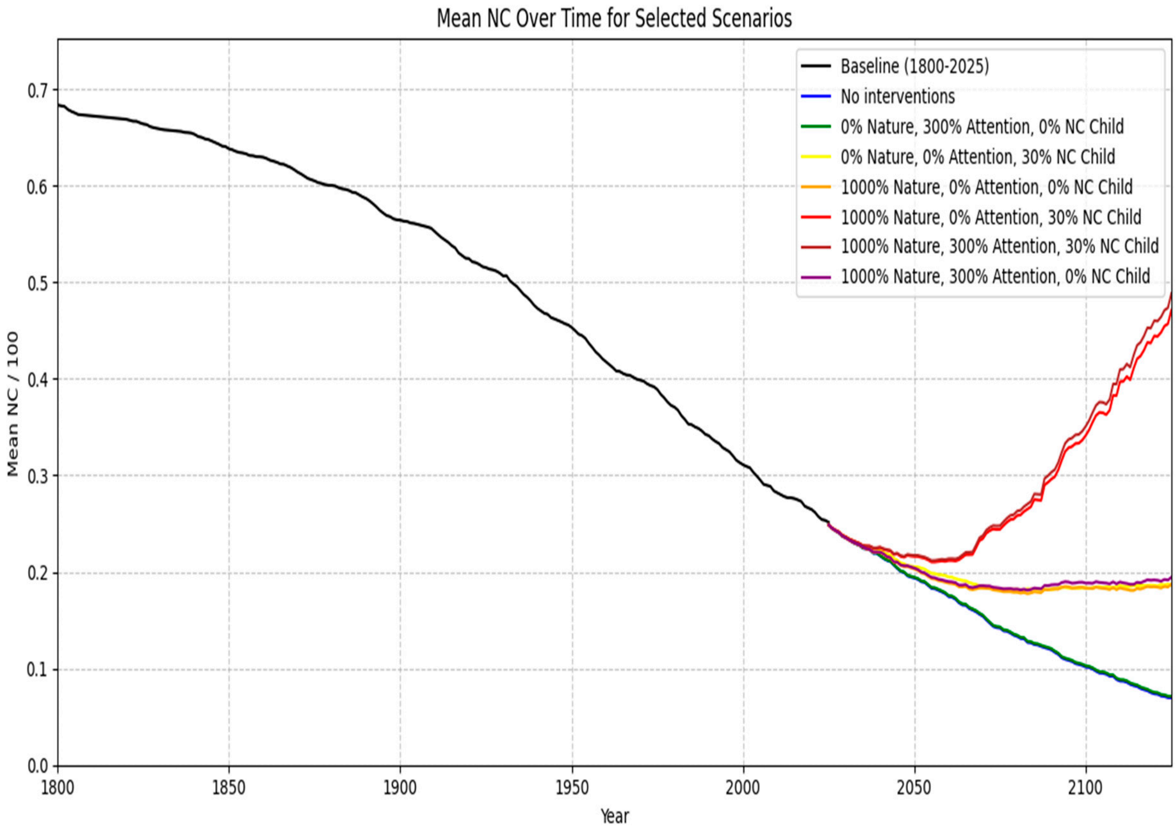

Figure 6. Future scenarios of nature connectedness to 2125.

4. Discussion

This study employed a hybrid, data-driven ABM to simulate the long-term dynamics of nature connectedness from 1800 to 2020. By modelling individual agents with life cycles, reproduction, and migration within an evolving environment shaped by urbanisation and nature degradation, the ABM successfully captured emergent, population-level trends such as long-term decline and generational compounding of disconnection. The model simulated a substantial decline in nature connectedness, primarily driven by intergenerational transmission mechanisms operating within increasingly urbanised and ecologically degraded settings. Projections to 2125 further underscored the difficulty of reversing this decline, with future trajectories clustering into three distinct patterns. The following discussion addresses each research question in turn, before considering implications for transformative change, recommendations, limitations and future research.

4.1. RQ1: Can an Agent-Based Model Replicate the Evolution of Nature Connectedness from 1800 to 2020

The ABM achieved high accuracy, with an RMSE of 0.0440 between nature connectedness and target, validating its ability to replicate historical nature connectedness trends. The sensitivity analysis confirmed robustness to changes in the saturation factor and number of families at initialisation. There was high sensitivity to parent weight, indicating that intergenerational transmission is critical for model fit.

Although the RMSE indicated strong model fit, the nature connectedness decline of 61.5% slightly exceeded the target range, 60.58% maximum in 1990, and the model missed the uptick to 52.39% at 2020. For context, in a cross-sectional survey of 63 nations, nature connectedness in the USA was 57.5% below the nation with highest level, Nepal, relative to the full range [33]. This suggests the modelled decline is plausible, though it may slightly overestimate the historical trend. Missing the uptick suggests either an issue with the nature connectedness target data in recent decades, or that the model may be missing macro-level factors that have positively influenced nature connectedness in recent decades, or that the nature word frequency proxy is reflecting something different in recent decades.

There are a number of macro-factors that are associated with levels of nature connectedness [26]. Only one with a positive association with nature connectedness has seen a recent uptick, spirituality [34]. Perhaps a growing need for spiritual fulfilment has driven an increase in nature connectedness, or nature word use. Further, there has been a growth in eco-awareness and the nature writing genre in recent decades which could potentially increase the use of nature words [35–37]. However, such changes would need to overcome the rapid increases in factors with a negative relationship, such as the rapid penetration of smartphone technology [26]. Finally, although providing a valuable tool for research [28], the composition of the Google ngram corpus was adjusted in 2004 to include more scientific and academic texts [38]. However, this is contested [30] and it seems likely that this would reduce, rather than increase, the use of simple nature words. Given that a systematic review found a continued weakening of the human–nature relationship over time, with no clear uptick in recent generations [6], further research is needed.

While there is inherent uncertainty in using nature-related word frequency as a proxy for nature connectedness—given that linguistic trends may reflect broader cultural shifts or genre biases—the model's alignment with this proxy is nonetheless remarkable. The ABM, which simulates human interactions with nature in an increasingly urban environment, closely mirrors the historical use of nature words in cultural products. This strong fit suggests that the ABM captures meaningful socio-ecological dynamics, reinforcing the validity of its structure and assumptions. The ability of a simulation based on environmental exposure, attention, and intergenerational transmission to replicate linguistic patterns over two centuries highlights the robustness of the intergenerational extinction of experience framework. It also underscores the potential of ABMs to bridge psychological constructs and cultural indicators, offering a powerful tool for understanding long-term human–nature relationships.

4.2. RQ2: Role of Intergenerational Transmission

The model's calibration provides a critical insight into the primary drivers of historical nature connectedness decline. Intergenerational transmission emerged as the overwhelmingly dominant driver of historical decline from 1800 to 2020, with the lifetime extinction of experience mechanism providing a statistically distinct, yet marginal refinement to model fit. Firstly, the comparative analysis of two model configurations found that the secondary model without the explicit lifetime extinction of experience mechanism performed nearly as well as the full model. This suggests that while the lifetime extinction of experience mechanism holds conceptual validity and refines the model's fit, its quantitative impact in our current model is comparatively minor when compared to the profound, cumulative effect of reduced intergenerational transmission across generations.

Secondly, in the full model child nature connectedness was determined by an 80% weighting on parental nature connectedness. The sensitivity analysis revealed high sensitivity to this parent/environment ratio, with lower values (e.g., 50%) increasing nature connectedness decline to over 80% (1970–2020), with higher values reducing the decline, but worsening fit substantially. The optimal 80/20 underscores the dominance of familial transmission, consistent with findings that parental nature connectedness strongly predicts child nature connectedness [9]. This suggests that family-based interventions could disrupt the cycle.

This finding has significant implications for understanding and addressing nature connectedness decline. It underscores the paramount importance of early life experiences and family environments in shaping an individual's relationship with nature. If children are born with lower initial nature connectedness due to their parents' own reduced connection (influenced by urbanised environments), this effect propagates and compounds over generations. This mechanism creates a powerful intergenerational momentum that sustains the decline of nature connectedness, making it a challenge to reverse. In sum, the results indicate a nuanced interaction where foundational connectedness is largely inherited, but its trajectory can be subtly influenced by ongoing, direct experiences. This intergenerational momentum introduces a lag effect, whereby improvements in environmental conditions may take generations to translate into increased nature connectedness, due to inherited low orientation from previous generations; a shifting baseline in action. By quantifying the relative contributions of intergenerational and experiential mechanisms, the model advances the extinction of experience framework [3] from a conceptual to a testable, dynamic systems perspective. The results also align with Folke's resilience perspective by capturing non-linear dynamics, thresholds, and uncertainty [14]. Urbanisation feeds nature connectedness decline through intergenerational feedback loops and the interplay of gradual nature loss and intergenerational shifts reflect cross-scale interactions spanning time and space.

4.3. RQ3: Projected Trajectory of Nature Connectedness

The results highlight the challenge of reversing the decline in nature connectedness observed from 1800 to 2020, driven by a tenfold increase in urbanisation. Despite testing transformative interventions nature connectedness in 2050 remained below 2020 levels in the three scenario clusters. These findings underscore that even radical interventions struggle to counteract the legacy of historical nature loss. This supports the notion that a potential tipping point in human-nature disconnection could have been passed [11].

The continued decline, despite significant interventions such as 100% increase in nature access, suggests that the model captures the self-reinforcing feedback loop of decline, consistent with extinction of experience dynamics and the findings of Kamphuisen et al. [11]. Their analyses revealed that when urban greenspace availability falls below 23%, a vicious cycle emerges. The current simulation's rise in urbanisation reduced green space availability to 16% and corroborates Kamphuisen's threshold. This is further supported by the second scenario cluster—holding steady—which includes the transformational 1000% increase in nature access alone and together with a 300% increase in attention. Plus, the child-focused intervention alone and in combination with the lowest levels of nature access and attention interventions. The limited impact of these transformative interventions aligns with theories of social-ecological tipping points, where transformative changes in societal values or behaviours can lead to persistent shifts [14,39], either positive or negative.

Turning to the third and most promising cluster—transformative change—emerges when a 1000% increase in nature access is implemented together with the child-focused intervention, representing a combined strategy of environmental restoration and strengthened intergenerational transmission. This cluster reveals a critical insight: the rate of nature connectedness improvement accelerates post-2050, despite interventions being fixed at 2050 levels, demonstrating that the intergenerational extinction of experience framework can function as both a vicious and a virtuous cycle, depending on the direction of intergenerational influence. The delayed improvement in nature connectedness—emerging only after interventions were compled—highlights the system's inertia and the time-lagged nature of recovery, reinforcing the need for early and sustained action. These results underscore that intergenerational transmission, while a key driver of decline, can also serve as a powerful mechanism for recovery when positively reinforced.

4.4. What Is Transformational Change?

These findings return the discussion to the opening of this paper and the recognition that disconnection from nature is a causal issue in the environmental crises and transformative change is required [1]. The IPBES Transformative Change Assessment identifies nature connectedness as a key strategy for achieving the 2050 Vision for Biodiversity. The findings presented here support the report's conclusion that deep, systemic change is urgent, necessary, and challenging. Among the five core strategies outlined in the report, prioritising human–nature connectedness is essential. This requires embedding nature connectedness into education and urban planning, while promoting a broader understanding that human well-being depends on a healthy natural environment. Well-designed policies and a whole-of-government, whole-of-society approach is advocated.

This context fits the ten-fold increase in nature availability. Although these increases may seem unobtainable, they start from a low baseline. In the UK, which has similar levels of nature connectedness and urbanisation to the US, studies have found that over 92% of people's time is spent indoors or within a vehicle, with 7% outdoors, but half of that is in a continuous urban environment [40]. Further, Mears et al. found that the median amount of time spent in green spaces per day was 4 min 36 s [41]. Based on these findings a ten-fold increase in nature availability could potentially be achieved through spending 35% of the day outdoors or 45 min per day in greenspaces. These changes seem more achievable and help explain why smaller increases of 50% or 100% had limited impact—when starting from such a low baseline, even doubling access results in only marginal gains.

The second key driver of transformative change identified by this research is the need to address intergenerational transmission through interventions targeting both children and parents. This highlights the importance of embedding nature connectedness into educational systems and family life. Programmes fully integrated into schools, parental engagement initiatives, and community nature activities can help foster early-life experiences that build lasting connections with nature. By nurturing nature connectedness from a young age and supporting parents in modelling nature-oriented behaviours, such interventions can disrupt the cycle of disconnection and lay the foundation for a more resilient, nature-connected society. Such foundational shifts are essential for achieving the scale of transformation needed to restore human–nature relationships and support long-term sustainability.

4.5. Recommendations

While this study is based on a single model of a complex relationship, its findings reinforce and expand upon previous research into strategies for improving nature connectedness—particularly the importance of increasing opportunities to access vibrant natural environments [42]. However, this study also provides a reminder of the historical and global context, that societies such as the UK and US have nature connection levels approaching 50% below the most connected nations and over 50% below where they were two centuries ago–and thereby the need for transformative change [1]. The specific ten-fold increase in the future scenario may well be an inaccurate target, but it is an indicator of the scale of change required to overcome one of the side-effects of centuries of transformational economic, technological and environmental change.

In addition to highlighting the scale of change required, this study shows that the decline in nature connectedness is not merely an individual issue. It is a systemic phenomenon, deeply rooted in long-term demographic and environmental shifts. This highlights the importance of sustained, long-term policy interventions to shift population-level trajectories through systematic approaches across the public realm [42]. These long-term and deeply embedded policies and interventions aimed at fostering nature connectedness should prioritise intergenerational engagement through educational programmes, community initiatives and familial nature experiences that empower parents and families to connect with nature, alongside transformative urban greening and access and engagement with.

Although reversing the long-term decline will take time, the model's projection of a "self-sustaining and accelerating recovery" post-2050 is a critical insight. It demonstrates how, once a threshold is crossed, interventions can trigger a positive feedback loop that propagates through the population. Finally, such interventions will also deliver short-term benefits. Although the lifetime extinction of experience mechanism was not the primary driver over generations, it should be remembered that increased engagement with nature can deliver sustained benefits in mental wellbeing [5,21] and mainstreaming such interventions will reinforce intergenerational transmission in cultural ways not captured in the current model.

In this context, the ABM approach offers a valuable tool for informing policy design and supporting a whole-of-society strategy to restore nature connectedness. For now, key recommendations emerging from this work are proposed below.

4.5.1. Strengthen Intergenerational Transmission Through Parental Engagement Programs

The analysis underscores the pivotal role of intergenerational transmission and parental influence, consistent with previous research [9,22]. Recommended policy actions include:

- Programs for new parents to boost their nature connectedness and their own self-efficacy and confidence in nature [43] at a time when young children are experiencing the wonder of nature for the first time.
- School curriculum that embeds nature engagement and the pathways to nature connection into teaching [44].
- Integrate nature connectedness into family-oriented policies, such as facilitating nature-engaged family outings or parenting resources emphasising nature's well-being benefits.
- Large scale public awareness campaigns to encourage familial engagement with nature based upon the pathways to nature connectedness [42].
- Leverage social learning by creating peer networks for parents to share nature engagement strategies, enhancing cultural transmission of nature connectedness [14].
- Support community-led initiatives in urban neighbourhoods to foster local stewardship and nature connectedness, leveraging social networks.

4.5.2. Transform Urban Greening and Access

There are many existing policy proposals for urban greening and access to nature, however the present study, supported by Kamphuisen's findings, highlight the scale of transformation required to overcome tipping points and a shifted baseline [11]. Urban settings are associated with the decline in nature connectedness [13] and urbanisation has increased ten-fold and continues to increase. Integration of nature access across the public realm is needed. Policy actions could include:

- Transform high-quality urban greening in city planning, focusing on biodiverse, accessible greenspaces (e.g., parks, green corridors) to maximise engagement opportunities.
- Transform the amount of time people spend in nature through the design of greenspaces and integration of nature access across the public realm, for example in education, health, transport, arts and housing [1].

4.5.3. Implement Adaptive Governance for Transformative Change

While many policy measures already support urban greening and nature access, this study highlights the scale of transformation required to overcome ecological tipping points and a shifted baseline. Folke warns that socio-ecological systems can cross thresholds into undesirable states and highlights the need for flexible, collaborative and innovative governance, involving social learning, visioning, and incentives to navigate these dynamics [14]. These findings, together with the results of the present study, suggest that steady-state policies are insufficient to address the scale and complexity of the challenge. In this context policy action may include:

- Establish multi-stakeholder platforms (e.g., city councils, NGOs, communities) to envision and co-design large scale nature connectedness interventions, integrating urban planning, education, and health policies [1].
- Develop incentive structures for nature rich developments or community-led rewilding, to stimulate adaptive responses to nature loss.
- Use visioning and scenario planning to model future nature connectedness trajectories under different greening and attention scenarios, informing long-term policies [1].

4.5.4. Monitor and Evaluate Nature Connectedness over Time

While this study relied on proxy data to model historical trends, the importance of long-term empirical tracking is increasingly recognised. The People and Nature Survey has already begun to fill this gap by monitoring nature connectedness across the UK population [45]. However, to fully support adaptive governance and systemic transformation, monitoring must be expanded and embedded within policy frameworks.

Drawing on Meadows' concept of leverage points in complex systems [46], timely and accurate data on nature connectedness can serve as a powerful feedback mechanism. By tracking changes across demographics and regions, such data can inform early interventions, identify emerging tipping points, and reinforce positive feedback loops that accelerate recovery. Recommended actions:

- Expand and institutionalise national and local monitoring systems for nature connectedness [26,42].
- Integrate nature connectedness indicators into broader wellbeing, education, and environmental reporting frameworks.
- Use real-time data to inform adaptive policies, enabling iterative learning and refinement of interventions aimed at restoring human–nature relationships.

In sum, the current research shows how the human-nature relationship is characterised by non-linear dynamics, thresholds, and feedback across temporal and spatial scales. Therefore, the recommendations outlined above must be implemented in an integrated and coordinated manner. Recent research has also shown non-linear synergistic and compensatory relationships between nature connectedness and nature access for outcomes of mental wellbeing and pro-nature behaviours [47]. Urban greening will have limited impact without addressing family engagement and intergenerational transmission. Finally, interventions should be context-sensitive, addressing disparities in access to nature and cultural differences in nature engagement, particularly in underserved or marginalised communities.

4.6. Limitations

Several limitations should be considered. The model's use of a fixed urbanisation trajectory and nature loss rate enhances ecological validity by aligning with historical trends. However, this approach limits the ability to simulate bidirectional feedbacks—such as how increased nature connectedness might influence conservation behaviours or land-use decisions. While future scenarios partially address this, dynamic feedback loops remain underexplored. The model's simplified 40 × 40 grid structure, while computationally efficient, abstracts away real-world spatial heterogeneity. This may obscure important local variations in urban–nature dynamics, such as differences in greenspace access across neighbourhoods or regions. The use of nature-related word frequencies as a proxy for historical nature connectedness—necessitated by the lack of long-term empirical data—introduces uncertainty in trend validation and model calibration. The model may underestimate the potential for recovery, particularly in response to large-scale interventions that significantly enhance nature availability or engagement. As a result, the projected effectiveness of such interventions may be conservatively biased. While the model highlights intergenerational transmission as a dominant driver, this emphasis may overstate its influence. In reality, broader macro-level factors—such as economic development, technological change, and cultural shifts—also shape nature connectedness and may moderate or amplify parental effects, although these additional macro-factors correlate highly with urbanisation [48]. Which presents a final limitation, the correlation between urbanisation and other macro-level variables—such as economic growth, scientific advancement, technological adoption, and even humanistic values [48,49]. This overlap may obscure the independent effects of these factors, potentially oversimplifying the complex drivers of human–nature disconnection. Finally, in the future scenarios, the model assumes that increased nature access translates into increased engagement. However, in reality, individuals' ability to act on this access may be constrained by the legacy of disconnection and structural factors such as time poverty, safety concerns, or cultural and social norms. These constraints are not explicitly modelled, potentially overestimating the behavioural response to access improvements.

4.7. Future Directions

This study demonstrates the value of agent-based models (ABMs) for exploring the long-term dynamics of human–nature relationships. Future research should build on this foundation by developing more complex and ecologically valid models that address current limitations and expand the scope of inquiry. First, spatial realism could be enhanced through the use of spatially explicit models incorporating real-world geographic data, such as urban land-use maps. This would allow for the capture of regional variation in greenspace access and enable validation against contemporary survey data. Second, future models should incorporate bidirectional feedbacks, where increased nature connectedness leads to pro-nature behaviours—such as conservation, advocacy, or stewardship—that in turn influence environmental conditions. However, given the small effect size of the lifetime feedback and complexity of transition from individual behaviours to transformative policy interventions, such advances would require further research to inform the implementation. Third, the model could be extended to include social diffusion mechanisms, where individuals influence others beyond their immediate family. This includes peer networks, educators, and community leaders who may amplify nature connectedness through cultural transmission. Such mechanisms are particularly relevant in scenarios involving large-scale access improvements, where individual action may precede policy change. Finally, integrating dynamic social influences (e.g., media campaigns, cultural trends), diverse nature types (e.g., forests vs. urban parks), and macro-level drivers (e.g., economic development, technology) would help balance the current emphasis on parental influence and better reflect the complexity of socio-ecological systems. Testing hypothetical scenarios—such as targeted family-based interventions or widespread urban greening—can further guide policy design to support transformative change for urban sustainability and human well-being.

5. Conclusions

This study's agent-based model illuminates the profound decline in nature connectedness from 1800 to 2020, driven by urbanisation and environmental degradation and intergenerational transmission of the extinction of experience cycle. By simulating these dynamics over more than two centuries, the model offers a novel systems-based perspective on the socio-ecological drivers of human–nature disconnection. Despite transformative interventions, projections to 2125 reveal a persistent disconnect through to 2050, underscoring a locked-in socio-ecological tipping point. A key insight is the dominant role of intergenerational transmission in sustaining this decline, highlighting the importance of early-life and family-based interventions. The model also reveals significant system inertia, with recovery lagging decades behind intervention—emphasising the need for urgent, sustained action.

Notably, the model's ability to closely replicate historical trends in nature word use—despite the uncertainties of using linguistic data as a proxy—demonstrates its robustness and empirical relevance. That a simulation based on environmental exposure, attention, and intergenerational dynamics can mirror cultural expressions of nature over two centuries is remarkable. This alignment reinforces the model's capacity to capture the socio-ecological dynamics underlying human–nature disconnection.

While the model simplifies certain spatial and social dynamics, it provides a foundational platform for future extensions, including spatial realism, social diffusion mechanisms, and bidirectional feedbacks between nature connectedness and environmental change. The integration of cultural indicators, such as nature word frequency, also opens new avenues for linking psychological constructs with long-term societal trends.

These findings highlight critical connections among environmental systems, where human-made risks like urban sprawl erode human–nature interactions, threatening urban sustainability and human well-being. The model's insights advocate for transformative policies to break the cycle of disconnection. By integrating nature connectedness into education and urban planning, societies can address global environmental changes and promote pro-environmental behaviours. This innovative modelling approach offers an initial blueprint for systemic change, aligning with the urgent need for a whole-of-society effort to restore human–nature relationships and ensure sustainable, thriving ecosystems. As societies confront the twin challenges of ecological degradation and psychological disconnection from nature, this model offers a timely and actionable framework for guiding transformative change.

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