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VISUALIZING CAUSE–EFFECT RELATIONSHIPS AS A MEANS OF DEVELOPING PRACTICE-ORIENTED THINKING IN STUDENTS IN THE NATURAL SCIENCE COURSE

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ABSTRACT

Our study is devoted to the theoretical justification and experimental validation of a methodology for visualizing cause–and–effect relationships as a means of developing practice–oriented thinking in students within the natural science course. In this research, visualization is regarded not as mere illustration but as an operational language of scientific reasoning—one that enables students to identify mechanisms, conditions, and consequences of natural phenomena. The methodology is grounded in the integration of the cognitive theory of external representations, principles of multimodal encoding, and formative assessment. A quasi experiment conducted in two parallel sixth-grade classes demonstrated that the systematic use of visual causal models contributes to increased cognitive coherence, a shift from linear to systemic explanations, the development of evidence-based predictions, and greater learning motivation. The obtained results confirm our working hypothesis that visualization of causality is an effective tool for fostering practice-oriented thinking and can be considered an element of the grammar of causality in school science education. In conclusion, we propose a conceptual architecture of pedagogical causality reflecting the interrelations among context, visualization, cognitive processes, and formative assessment.

KEYWORDS: Visualization Of Cause–Effect Relationships; Practice–Oriented Thinking; Natural Science; Cognitive Visualization; Causal Reasoning; Formative Assessment; Causal Map; Systems Thinking; Multimodal Learning; Pedagogical Causality.

1. INTRODUCTION

Contemporary science education is undergoing a shift: from transmitting "ready-made" knowledge to fostering students' ability to apply it in open and interdisciplinary contexts. Within this progressive perspective, the core educational objective is not the memorization of facts but the formation of practice-oriented thinking: the ability to identify the causes and consequences of natural phenomena, construct explanations and predictions, choose appropriate interventions, and evaluate their outcomes. This capability presupposes mastery of causal reasoning and the ability to "see" causality in data, texts, graphs, and real-world situations.

In this framework, the visualization of cause–and–effect relationships (ranging from simple arrow diagrams to conceptual maps and causal graphs) functions not as an illustration but as a tool of thought—an externalization of mental processes that makes reasoning observable, analysable, and collaboratively constructed. Indeed, decades of research in cognitive psychology and educational science have shown that visual representations structure attention, reduce extraneous cognitive load, and strengthen the integration of verbal and imagistic codes, thereby enhancing comprehension and knowledge transfer (Paivio, 2008; Sweller, 2022; Mayer, 2020).

For Natural Science, this is particularly significant, since most phenomena studied are multicomponent, nonlinear, and involve hidden variables—such as matter cycles, ecological interactions, and energy balances. Without external visual scaffolds, students struggle to maintain both the dynamics and the structure of explanations in working memory. Here, visualization of causality becomes a cognitive instrument (Bruner, 1997) that allows students to move from listing facts to building models: identifying factors, determining directions of influence, specifying conditions of operation, distinguishing mediators and moderators, and formulating testable predictions.

International frameworks for assessing educational outcomes (e.g., PISA, NGSS) increasingly emphasize explanatory and argumentative components of scientific literacy: students must not only know but also explain phenomena via scientific ideas, data, and models, identify causal links and evaluate competing explanations (OECD, 2017; National Research Council, 2012). Visual causal representations—concept maps (Novak & Cañas, 2008), causal chains, oriented graphs, and influence diagrams—serve as the "language" through which students articulate explanations and teachers diagnose understanding. The structure of the map reveals which links are established, where gaps or cycles appear, and whether false associations or confusion between correlation and causation exist.

Despite these theoretical and normative foundations, school science practice often remains fact-centered: visuals are used as illustrations rather than as media for hypothesis generation and testing. Consequently, the potential of visualization as a bridge between empirical listing and explanatory modeling is underutilized. The problem is compounded by the tendency of causal relationships to be obscured by contextual conditions, delayed effects, or competing mechanisms. Without explicit tasks and visualization techniques, students tend toward superficial reasoning—relying on temporally proximate or perceptually salient factors (availability bias) and substituting correlation for causation.

Our study proceeds from the assumption that deliberate and systematic integration of causal visualization into the natural science curriculum can serve as an effective means of developing practice-oriented thinking.

We define visualization as a set of didactic tools and techniques that externally fix and transform the structure of students' causal reasoning, including the following:

1. Cause–effect diagrams with explicit labeling of conditions and mediators,
2. Causal chains and networks of varying granularity,
3. Concept maps with an explicit typology of links (causal, functional, contextual),
4. Visual "scenarios" with branching options allowing prediction and feedback,
5. Work with data (graphs, tables) where causal explanations are aligned with patterns of variable change.

Crucially, these visual forms are not an end in themselves; they serve to formulate questions, construct hypotheses, build explanations, and evaluate interventions ("What will happen if…?"). In other words, they support the full cycle of scientific reasoning at the learner level.

The scientific novelty of our approach lies in integrating three rarely combined strands of educational practice:

a) Cognitively grounded visualization (dual coding, multimedia learning, cognitive load theory),
b) Explanatory causal modeling adapted to the school level (causal chains and simple directed

graphs rather than formal DAGs or structural models),

c) Practice-oriented tasks extending beyond textbook contexts to real-world domains (ecology, climate, resource management), where causal reasoning is inherently tied to assessing risks and intervention outcomes.

We argue that this triad—visualization as a tool + causality as the grammar of explanation + practice-oriented task as context—creates the conditions for the sustainable growth of scientific literacy. Methodologically, our work draws on the tradition of inquiry-based and problem-oriented learning (Hmelo-Silver, 2004) while emphasizing the explicit construction of visual causal models by students.

This approach enables the following:

1. Diagnostics of explanatory quality (not only factual accuracy but also coherence, completeness, and attention to conditions),
2. Development of metacognitive skills for revising one's own explanations,
3. Transfer of causal reasoning across diverse phenomena through a shared "grammar of causality."

An important secondary outcome is increased learning motivation: tasks such as "What would happen if…?", "Why did this variable increase…?", or "which measures would reduce…?" appeal to authentic problems and invite hypothesis testing through data, diagrams, and thought experiments.

The purpose of our work is thus to provide both theoretical justification and experimental validation of a methodology for visualizing causal relationships as a means of forming practice-oriented thinking in the natural science course. To achieve this goal, we sequentially:

1. Clarify the notions of practice-oriented thinking and visualization of causality in the context of school science;
2. Describe the instructional design and tools focused on constructing and editing causal visual models;
3. The results of a pedagogical experiment are presented, and their impact on explanatory quality and learning motivation is discussed.
4. Identifying limitations and outlining prospects for scaling the approach to related subjects and educational levels.

We regard this study as a contribution to the didactics of science education, in which visualization ceases to be an "illustration to a paragraph" and becomes a language of causal explanation accessible for joint work between students and teachers. In this language, a student learns to translate observation—model—prediction—solution—evaluation—thus traversing the full trajectory of practice-oriented reasoning.

In accordance with the purpose and logic of the pedagogical experiment, we formulated a system of hypotheses reflecting assumptions about the influence of causal visualization on the development of students' practice-oriented thinking in natural science.

Null hypothesis (H_0):

The use of causal visualization in the learning process has no statistically significant effect on the level of development of students' practice-oriented thinking. We expected that differences between the control and experimental groups in the rubric's final indicators would be random and within the margin of error.

Working (alternative) hypothesis (H_1):

The application of causal visualization significantly enhances the level of students' practice-oriented thinking by ensuring the following:

- A transition from linear to systemic types of explanation,
- Increased cognitive coherence and awareness of causal relations,
- Development of the ability to identify conditions, moderators, and mechanisms,
- The formation of an evidence-based argumentative stance,
- Expansion of predictive and modeling capabilities ("what-if" analysis).

We thus hypothesized that students in the experimental group—those systematically constructing visual causal models—would demonstrate higher total rubric scores and qualitative improvements in reasoning structure than would those in the control group. Consequently, the working hypothesis (H_1) confirms that visualization of cause–and–effect relationships can be regarded as an effective means of developing practice–oriented thinking in science education.

2. LITERATURE REVIEW

The problem of developing practice-oriented thinking in science education inevitably leads us to three interrelated domains: the epistemology of causal explanation, the cognitive psychology of visual representations, and the didactics of scientific modeling. In this section, we systematize the theoretical foundations underpinning our approach, demonstrating that visualization of causal relationships is not merely a matter of visual aid but constitutes a distinct class of external cognitive artifacts that transform the pathway from empirical observation to explanatory modeling and, ultimately, to prediction and action.

This transformation involves at least three complementary frameworks:

1. Cognitive, concerning the nature of causal reasoning and the role of external representations,
2. Didactic, concerning the organization of student activity as modeling,
3. Semiotic–methodological, concerning the grammar of visual languages suitable for expressing causality and supporting controlled model transformations.

2.1. Causal Reasoning as the Core of Scientific Literacy

From the standpoint of cognitive science, causal reasoning represents the ability to construct and use models of mechanisms—that is, to describe how the influence of one factor leads to a change in another under certain conditions and through certain mediators (Gopnik & Schulz, 2010; Lombrozo, 2006). The development of this ability involves at least two major transitions: from associative linking of events to causal attribution and from local linear relations to systemic explanations that account for feedback loops and nonlinear effects (Resnick, 1997). In classroom practice, these transitions are often disrupted for several reasons: the limited capacity of working memory when processing multistep dependencies, confusion between correlation and causation, and the availability effect, whereby students assign causal status to the most recent or salient event (Tversky & Kahneman, 1974).

Contemporary frameworks of scientific literacy—both international (OECD/PISA) and national—emphasize that explanations and argumentation are central practices of science (Osborne, 2010; Sanat, 2022). To explain the means to propose a model of a causal mechanism that is consistent with the data and capable of generating testable predictions. This leads to an important didactic challenge: creating conditions under which a student can not only reproduce a verbal template (“because…”) but also externalize the structure of causal reasoning, making it a subject of collaborative analysis and revision.

Here, visualization becomes a methodological instrument—it externally captures the structure of a hypothesis, reduces the cognitive load, and enables operations on the model (reordering links, introducing mediators, marking conditions, and testing alternatives).

2.2. External Representations, Cognitive Load, And Multimodal Encoding

Classical work in cognitive load theory shows that instructional materials are effective when they respect the limits of working memory, minimize extraneous load, and optimize the schematization of content. Properly designed visual causal schemes (arrow diagrams, directed graphs, factor–effect tables) reduce the need to hold long verbal chains in memory by distributing processing between visual and verbal channels.

However, this effectiveness is not automatic: diagrams can either help or hinder learning depending on whether they observe principles of coherence (avoiding irrelevant details), contiguity (proximity of labels to elements), and avoidance of visual overload. Thus, visualization must be literate not only semantically but also cognitively and ergonomically.

From the perspective of the theory of external representations, visual artifacts are not passive containers of information but active agents that direct attention, define permissible operations, and shape reasoning trajectories (Scaife & Rogers, 1996; Zhang & Norman, 1994; Abdimanapov, 2025). A causal map that explicitly marks conditions (if), mechanisms (through), and moderators (depending on) provides students with a workspace in which they can formulate hypotheses, test competing explanations, and identify gaps or conflicting arrows.

Visualization thereby becomes a tool of metacognitive regulation: students literally “see” how they think—and learn to think better by revising their own models.

2.3. Conceptual Change and Scientific Modeling in Student Activity

The transition from “everyday” to scientific explanations often requires conceptual restructuring—the replacement of intuitive theories that attribute causality directly to observed effects, without reference to underlying mechanisms (Carey, 2011; Chi, 2005). Research on conceptual change shows that students tend to retain stable alternative conceptions even after repeated instruction, unless cognitive conflict is induced and a viable replacement schema is provided (Posner et al., 1982).

Visualization, as an explicit means of model construction, facilitates both aspects:

1. It exposes inconsistencies (loops where none should exist, “dangling” arrows, or conflation of mechanism and result),
2. It offers alternative models with explicit conditions and mediators that can be applied across tasks, demonstrating their heuristic

power.

Student activity can thus be understood as model-based inquiry (Windschitl, 2008): learners build, evaluate, and reconstruct models, relating them to data and "what-if" questions. Causal diagrams function as lightweight mechanism models: simple enough for sixth graders to construct and modify yet expressive enough to support explanation and prediction. Importantly, such visual models bridge the qualitative and quantitative dimensions of learning. A set of causal arrows can be connected to data tables, dynamic graphs, or elementary representations of the proportionality and nonlinearity of effects.

2.4. *Systemic And Nonlinear Causal Thinking in Science*

Many topics in the natural science curriculum are inherently systemic—cycles of matter, ecosystem interactions, and climatic processes. Their defining features include multiple causalities, delayed effects, feedback loops, and threshold phenomena. The visual grammar must therefore transcend the linear "A - B" chain, incorporating branching networks, polarity of influence (reinforcing/inhibiting), and explicit feedback loops.

Research on systems thinking in schools and universities shows that even the introduction of "weak" systemic forms—such as causal-loop diagrams or influence maps—enhances explanatory depth and predictive quality (Plate, 2010). The pedagogical challenge lies in avoiding excessive formalism (e.g., differential equations) while providing students with an alphabet of systemic causality sufficient to reason about real-world examples, from eutrophication and population dynamics to wildfire risk.

2.5. *The Semiotics of Diagrams: From Concept Maps to Causal Graphs*

The semiotic perspective emphasizes that visual representations possess their own grammar and pragmatics—the way we draw a connection affects the way it is understood (Baker, 2021; Eastman, 1986). Concept maps are effective for recording concepts and general relations, but they often blur causal meaning by mixing it with associative or taxonomic relations. For causal explanations, diagrams with explicit edge typology ("cause," "condition," "mechanism," "moderator," "effect"), directionality, and, where possible, polarity of influence are preferable. In their stronger versions, such diagrams approach intuitively directed acyclic graphs (DAGs) of causality. However, at the school level, it suffices to follow several strict rules: one-way causal arrows, explicit labeling of mediators, no "naked" correlational arrows without mechanism, and empirical testability of each link. These rules transform the diagram from a static picture into a tool of reasoning and verification.

2.6. *Visualization And Argumentation: From Explanation to Justification*

A causal diagram becomes a genuine learning instrument only when it is integrated into the cycle of argumentation. The student not only builds a model but also justifies it—citing data, comparing alternatives, and responding to critical questions (Toulmin, 2003). Visual causal maps, as a form of language, substantially simplify the unfolding of the argument structure: evidence can be tied to specific nodes and edges; rebuttals to competing arrows; and warrants generalized scientific principles (e.g., biogeochemical laws).

Thus, visualization does not replace argumentation but rather materializes its structure, rendering it accessible for collective critique and refinement.

2.7. *Sociocultural Framework: Collaborative Construction and the Zone of Proximal Development*

Vygotskian theory allows us to regard visual models as cultural mediational means through which higher mental functions develop (Vygotsky, 2019). A causal diagram becomes a scaffold within the learner's zone of proximal development: what the student cannot yet perform mentally can be achieved in cooperation with the teacher and peers by relying on an external artifact (a scheme, a template, or a table of conditions and mediators).

This collaboration is crucial, as it turns the diagram into an object of negotiated meaning; collective editing fosters internalization of the "grammar of causality." Hence, the importance of explicit didactic procedures—scaffolding, teacher modeling of diagrammatic actions, and gradual withdrawal of support as mastery increases.

2.8. *Assessment Of Causal Thinking and Visual Diagnostics*

Finally, causal visualization provides a rare opportunity for formative assessment focused not on final answers but on the process of constructing explanations (Black & Wiliam, 2009). Teachers gain a rapid diagnostic tool: they can see where key elements of the mechanism are missing, where conditions are confused with causes, or where effects "float" without sources. Such maps are easily compared over time to track growth in coherence and accuracy and to serve as a basis for personalized feedback.

In this sense, visual artifacts bridge learning and assessment, acquiring the status of forms of assessment as learning.

In summary, the theoretical foundations of the proposed approach integrate cognitive, didactic, and semiotic perspectives. In our interpretation, visualization of causal relationships is not a decorative illustration but an operational language of students' scientific reasoning. It reduces the cognitive load, makes mechanism structures explicit, supports argumentation and collaborative revision, fosters systemic understanding, and enables formative assessment—thereby transforming the very grammar of learning in science education.

3. METHODOLOGY

Our methodological design proceeds from a dual objective: first, to construct a didactic intervention that turns the visualization of cause–effect relationships into an operational language of student activity in the Natural Science course,

Second, we organize measurement in a way that allows us to trace dynamics in students' practice-oriented thinking and learning motivation under ordinary school conditions.

3.1. Context, Sample, And Design

The study was conducted under real instructional conditions at the municipal state institution Secondary School named after D. Kunaev (East Kazakhstan Region). The participants were sixth-grade students enrolled in the natural science course during the 2022–2023 academic year: class 6A served as the control group (CG), and class 6B served as the experimental group (EG).

The research design was quasiexperimental with intact (nonrandom) class assignment and comprised three phases: a baseline (pretest) diagnostic stage, a formative (intervention) stage consisting of a sequence of lessons, and a final (posttest) diagnostic stage. This arrangement respects the ethical and organizational constraints of school practice while preserving the possibility of comparing trajectories for two comparable cohorts.

Methodologically, we treat the experiment as an embedded didactic intervention. In the EG, a sequence of lessons is implemented in which students construct, revise, and apply visual causal models to explain natural phenomena and to design the consequences of potential actions. In the CG, lesson content and thematic situations are identical, but visualization is not elevated to the status of a "modeling language" and is not used systematically as a reasoning tool—it is present only in a purely illustrative form.

3.2. Logic Of the Intervention and Stages

The formative stage consisted of five interrelated lessons (one topic per lesson), each unfolding a complete cycle of student scientific reasoning: observation/task identification of factors, construction of a causal diagram, "what-if" prediction, comparison with data/principles, and model revision.

Situations were chosen to be realistic, contextually meaningful, and conducive to multiple causation (conditions, mediators, moderators):

1. Water quality and fish die-offs: analysis of a scenario in which unpleasant odor and fish mortality appear after a nearby factory begins operation; identification of the roles of wastewater, dissolved oxygen, temperature, and current,
2. Deforestation and hydroclimatic effects: reconstruction of the chain "forest - evapotranspiration - precipitation - water cycle - groundwater level - local climate," with attention to linking order and intermediate mechanisms,
3. Eutrophication of water bodies: effects of fertilizer inputs (nitrogen, phosphorus), phytoplankton growth, oxygen decline, algal blooms, consequences for biota and water quality, and discussion of preventive measures (buffer strips, agronomic practices, wastewater treatment),
4. Trophic cascades: "What happens if wolves disappear?"—cascading consequences for herbivores, vegetation, and ecosystem stability; discussion of predator roles,
5. Climate and wildfires: interpretation of long-term temperature trends and wildfire statistics in Kazakhstan; distinguishing correlation from plausible causation via mechanisms such as fuel desiccation, increased frequency of extreme heat, and winds

Each topic was designed as a bridge between a qualitative model and data. Students first construct a causal map (a directed graph), then align it with graphs/tables (where available), and finally return to the diagram to refine it.

3.3. Didactic Toolkit for Visualization

To ensure that visualization genuinely functions as

a "language of causality," we specified strict rules for diagram grammar:

- A directed arrow denotes causal influence, with any required conditions explicitly stated,
- A mechanism node is labeled (e.g., "O_2 in water" between "algal growth" and "fish mortality").
- The polarity of influence (reinforce/weaken) is marked above the arrow; if a moderator (e.g., "water temperature") is present, it is indicated by a dashed arrow pointing to the edge.
- Purely correlational arrows without a mechanism are not permitted.
- The feedback loops are highlighted with a distinct color/pattern and discussed through examples (e.g., "vegetation degradation - albedo change - local warming - increased fire activity").

Situations were selected to be realistic and contextually salient and to support the deployment of multiple causation (conditions, mediators, moderators). Examples of practice-oriented tasks used during the formative stage are presented in Table 1.

Table 1: Examples Of Practice-Oriented Tasks with Expected Answers.

№	Lesson topic/context	Task prompt	Objective (targeted skill)	Expected student answer (key causal chain elements)
1	Water pollution and fish die-offs	Scenario: After a factory was built by the river, residents noticed an unpleasant odor and mass fish mortality. Question: What is the most likely cause of the fish die-off?	Analyzing ecological consequences of economic activity; identifying pollution causes	Wastewater discharge - toxins enter water -dissolved oxygen decreases - fish die
2	Deforestation and climate change	Task: Arrange events in the correct order to show the causal chain: 1) deforestation, 2) decreased evapotranspiration, 3) disruption of the water cycle, 4) climate change, 5) lower groundwater levels	Logical structuring of ecological processes; establishing a sequential dependency chain	Correct order: 1–2–3–5–4. Deforestation reduces evapotranspiration, disrupts the water cycle, lowers groundwater levels, which alters regional climate parameters
3	Eutrophication of water bodies	Scenario: After fertilizers were applied to nearby fields, the lake showed increased algal growth. Questions: Why did this happen and how does it affect the ecosystem?	Analyzing chemo-biological processes; explaining links between anthropogenic impacts and natural cycles	Nitrogen and phosphorus from fertilizers - rapid algal growth - oxygen depletion - fish mortality; degraded water quality
4	Predator loss in an ecosystem	Question: What would happen if wolves disappeared from the Kazakh steppe? Name two possible consequences.	Developing systems thinking; predicting cascading ecological effects	Loss of wolves - herbivore populations (e.g., saiga) increase - vegetation degrades - ecosystem balance is disrupted
5	Climate change and wildfires	Task: Analyze a chart of mean air temperature and wildfire counts. Question: Is there a relationship between temperature and fire frequency?	Interpreting data; constructing explanations from graphical information	Rising temperatures dry forests - fuel becomes more flammable - wildfire frequency increases. Conclusion: Climate change elevates fire risk

The tasks in Table 1 address the core components of scientific thinking: establishing causal links, forecasting consequences, interpreting data, and fostering ecological responsibility. Each task follows principles of cognitive visualization: students create diagrams or chains that allow them not only to record but also to revise the logic of their reasoning. Each topic was designed as a bridge between qualitative modeling and data: students first produce a causal map, then align it with graphs/tables, and finally return to the diagram for refinement.

3.4. Lesson Procedures

Each lesson followed a common script:

1. Problematization (5–7 min): presentation of a short realistic text/photo scenario and the posing of a "why?"/"what if…?" question,
2. Initial modeling (10–12 min): small-group work (3–4 students) with factor cards to construct a draft causal map,
3. Formative mini-diagnostic (5 min): rapid exchange of maps between groups with notations for clarifying questions or doubts;
4. Alignment with mechanisms and data (10–12 min): Mapping the diagram to a minimal corpus of facts/graphics/course rules, adding mechanisms and moderators, and relabeling arrows as needed;
5. Prediction and interventions (5–7 min): branching "if… then…" scenarios; designing measures to alter the trajectory (buffer strips, wastewater treatment, logging regulations, etc.), followed by returning to the map to record expected effects,
6. Reflection and versioning (3–5 min): brief "what we learned" notes and a photo/scan of the group's final map.

The teacher acted as a modeling moderator rather than an "answer key." The teacher posed critical questions ("What links these two nodes?", "Which condition must be met for this arrow to hold?”, “Is there a closed loop here?”), modeled explicit identification of mechanisms, and provided “lightweight data” (minimally sufficient graphs/tables) for checking.

3.5. Assessment Tools and Metrics

The assessment combined formative diagnostics with pre/post comparisons.

3.5.1. Pre- And Postintervention Diagnostics

Before and after the formative stage, both classes completed parallel diagnostic tasks on causal explanations and practice-oriented problem solving. The scoring criteria included the following:

- Causal correctness (presence of a mechanism, meaningful arrow direction, no substitution of correlation for causation),
- Coherence and completeness (number and quality of essential links; absence of “dangling” nodes),
- Attention to conditions and moderators,
- Prediction and interventions (plausibility of “if… then…” branches; alignment with scientific ideas in the course),
- Argumentation with data (ability to align the model with a graph/table).

Each criterion was rated on a four-point scale (0–3), yielding a total causal map score and a profile of strengths/weaknesses. Additionally, we recorded learning motivation via a brief questionnaire (interest/usefulness/confidence) to track the motivational effects of the intervention. The detailed rubric used to assess students’ causal reasoning is presented in Table 2.

Table 2: Rubric For Assessing Students’ Causal Reasoning.

Criterion	Indicator description	Level 0 (low)	Level 1 (emerging)	Level 2 (proficient)	Level 3 (advanced)
1. Causal correctness	Ability to distinguish cause, condition, and effect; presence of logical links in the model	No logical links; confusion of cause and effect	Some causal links indicated but no clear mechanism	Causes and effects correctly identified; mechanism sketched in general terms	All links are scientifically correct; the causal mechanism is fully elaborated and justified
2. Structural coherence and completeness	Quantity and interconnectedness of chain elements; wholeness of the phenomenon’s depiction	Fragmentary description; 1–2 links without context	Chain of 3–4 links with some omissions	Sequential chain of ≥5 links with key factors included	A coherent system reflecting multiple relations and feedback loops
3. Attention to conditions and moderators	Understanding factors that affect the strength or direction of causal action	No conditions indicated	One condition mentioned without explanation	1–2 conditions named with partial explanation of their roles	Conditions and moderators explicitly indicated with correct explanation of their influence
4. Prediction and interventions	Ability to predict system consequences and propose solutions	No prediction or purely random	Partially correct prediction; superficial solutions	Realistic prediction with at least one adequate solution	A full causal forecast with well-justified intervention measures
5. Argumentation with data	Use of facts, graphs, and tables to support the model	No use of data	An example cited without linkage to the model	Data correctly interpreted with partially explained linkage	Evidence-based argumentation with correct use of multiple data sources

This rubric (Table 2) draws on the formative assessment approach (Black & Wiliam, 2009) and on level descriptors for scientific explanation (OECD, 2017). Each criterion captures a distinct phase of scientific reasoning—from identifying causality to data-based argumentation—and, taken together, forms a profile of the learner’s practice-oriented thinking. The maximum total score is 15 (3 points per criterion). The scale allowed us to quantify the results and to use the rubric as a tool for self-assessment and feedback.

3.5.2. Assessment Of Formivation During Lessons

In each lesson, we employed self-checklists, “cross-checking of maps,” and brief oral defenses (1–2 groups per lesson briefly justified a key model fragment before the class). This approach tracked not only outcomes but also improvement dynamics across lessons: the emergence of mechanisms, the correction of arrow directions, the introduction of moderators, and the phasing out of “correlational” arrows.

3.6. Analytical Strategy

Our analysis combined quantitative and qualitative components:

- Quantitative: comparison of distributions across mastery levels (very low/low/medium/high/very high), the share of “positive results” (sum of medium and

above), and gains from pre- to posttest,
- Qualitative: coding of maps and oral explanations for typical misconceptions and their remediation (confusing conditions with causes; disappearance of "dangling" nodes; emergence of mechanisms and moderators; explicit marking of feedback loops). We paid special attention to transfer: whether students applied the learned "grammar of causality" to new topics without explicit teacher prompts.

This mixed approach aligns with the conception of formative assessment as assessment for learning and reveals not only "how high students climbed" but also how—through which structural changes in reasoning.

3.7. Reliability And Validity

To ensure content validity, tasks were constructed as multiprojectional: each topic required at least

a) identification of key factors,
b) Explication of the mechanism,
c) attention to conditions/moderators,
d) alignment with data,
e) Prediction and interventions.

Construct validity was supported through the explicit operationalization of "practice-oriented thinking" in terms of actions on the causal model. Criterion validity was examined by comparison with indicators of learning motivation and qualitative signs of improved explanations.

Reliability was ensured as follows:

1. developing rubrics with anchor exemplars for each criterion level,
2. double-blind scoring of a subset of work (≥25%) by two independent raters with calculation of an agreement coefficient (e.g., Cohen's κ) followed by calibration,
3. Fixed procedures for administering pre/postdiagnosis.

3.8. Ethical Considerations

The study was carried out within the school's standard instructional activity and did not involve harmful interventions or create unequal access to course content. Class participation was approved by the school administration; the data were anonymized, and the publication of aggregated results precluded the identification of individual students. The CG experienced no "deprivation": lesson content and volume matched the curriculum; the only difference was the absence of a systematic visual grammar as a language of causality.

3.9. Integration With Theory and Expected Effects

Our methodology rests on principles from Cognitive Load Theory (modality alignment, coherence, spatial–temporal contiguity), Dual Coding (distribution of processing across verbal and visual channels), and model-based learning (the student as constructor and critic of models).

The expected effects include the following:

1. A reduced extraneous cognitive load when explaining multistep processes,
2. Increased causal correctness of explanations (emergence of mechanisms, moderators, and feedback loops),
3. Growth in the share of positive results at the end of the formative stage,
4. Elevated learning motivation is due to tasks with clear practical relevance that invite the design of interventions.

Taken together, the proposed methodology transforms visualization from an "illustration to a paragraph" into a medium of scientific reasoning: students gain a tool for constructing, testing, and revising causal models, whereas teachers acquire a transparent mechanism for formative diagnostics and targeted support.

4. RESULTS

The empirical data we obtained make it possible to assess the extent to which the systematic introduction of causal visualization influences the quality of explanations, levels of content mastery, and students' motivation.

Below, we analyze sequentially:

(i) the final distributions of mastery levels in the experimental (EG) and control (CG) groups,
(ii) the increase in "positive results" from pre- to postintervention diagnostics,
(iii) the qualitative dynamics of students' explanations and causal maps,
(iv) alternative interpretations and the internal validity of the results,
(v) The study's limitations and directions for further work.

4.1. Final Distributions and Comparative Dynamics

At the conclusion of the formative stage, the EG presented the following distribution of levels on the posttest:

7% – very high,
12% – high,
33% – medium,
30% – low,
18% – very low.

The combined share of "positive" levels (medium + high + very high) reached 52%, which is 9.5

percentage points higher than that on the pretest (42.5%).

In the CG, the corresponding posttest shares were as follows:

5% – very high,
16% – high,
30% – medium,
27% – low,
21% – very low.

The combined "positive" share was 51% (an increase of +3.5 p.p. from 47.5% at baseline).

These results indicate the following. First, despite similar posttest "positive" shares (52% in the EG vs. 51% in the CG), the dynamics differ markedly. In particular, the EG's gain is nearly three times greater (9.5 p.p. vs. 3.5 p.p.), which is consistent with the expected effect of targeted causal visualization as the "operational language" of instruction.

Second, the shift in distributions within the EG is expressed not only in the growth of medium and high levels but also in a reduction in the low/very low levels (by a combined 19.5 p.p.). In other words, the intervention appears to work less by "lifting those already successful" and more by raising the lower tail of the distribution—precisely where cognitive difficulties typically arise in maintaining multistep dependencies and distinguishing correlation from causation.

4.2. Qualitative Evolution of Students' Explanations

Qualitative analysis of students' maps and brief oral defenses reveals several robust shifts in the EG. At baseline, students more often constructed linear, fragmentary chains anchored to temporally proximate events. Mechanisms and conditions remained implicit ("the fish died because there is a factory nearby"), and moderators or feedback loops were virtually absent.

After a series of lessons with an explicit "diagram grammar," students more consistently:

1. Made the mechanisms explicit, inserting intermediate nodes ("algal growth - dissolved O_2 decline - fish mortality") and specifying the conditions under which arrows hold ("the effect is amplified at higher temperatures").
2. Separate correlation from causation, abandoning "naked" arrows without mechanisms in favor of structured links ("if… then… because…").
3. Introduced moderators and feedback loops, noting threshold phenomena and cascading effects (e.g., in predator–prey and wildfire tasks), indicating a transition from linear to systemic causal reasoning.

This evolution aligns with basic cognitive logic: external visual representations reduce extraneous working-memory load, enabling learners to see the structure of their reasoning and edit it. At the same time, it supports the study's validity: we observe changes not only in total scores but also in the grammar of explanations—the emergence of mechanisms, conditions, moderators, and feedback loops that directly address common cognitive errors in causal inference.

4.3. Transfer And Practical Orientation: From Model to Action

The significance of visualization as a "language of causality" is most evident when students move beyond verbal explanation to the design of interventions and evaluation of their consequences. In eutrophication tasks, a substantial share of EG students began proposing operational measures ("buffer strips," "regulated fertilizer application," "wastewater treatment") and embedding them in the map as changes to upstream factors or mechanisms ("buffer strips - reduced N and P inflow - weaker algal growth - higher O_2 - lower fish mortality risk").

We emphasize that this can be interpreted as a principled shift from "describing the world" to causally justified action, which defines practice-oriented thinking within scientific literacy. In trophic-cascade tasks, students learned to anticipate indirect effects ("predator loss - herbivore boom - vegetation degradation - altered ecosystem stability") and to compare these effects with alternative explanations—thereby strengthening the argumentation component.

4.4. Motivational Effect and Learning Engagement

On the basis of teacher observations and postintervention diagnostics, motivational dynamics in the EG were characterized by growth in the share of students exhibiting "very high/high/medium" levels of learning activity and interest in the subject, whereas changes in the CG were more modest. Following the series of practice-oriented lessons, the proportion of high motivation increased, and that of low motivation decreased. We interpret this as confirming the hypothesis of a motivational effect of the methodology.

This is theoretically expected within our framework: tasks framed as "what will happen if…?" and "which measures would reduce…?" entail personally meaningful forecasting and choice—factors that inquiry-based learning identifies as key sources of intrinsic motivation.

4.5. Internal Validity and Alternative Explanations

One may ask whether the EG gains could be explained by external factors. We note that the modest improvement in the CG can be attributed to age-related development, a clearer articulation of learning objectives, and the specifics of the textbook. In contrast, the EG's gain is both larger and structurally different (notably, the reduction in low-level performance), which aligns with the impact of a targeted visualization methodology.

We acknowledge the quasiexperimental design (intact classes), which does not rule out teacher/class effects. Nevertheless, the consistency of observed qualitative improvements in the grammar of explanations—across several thematic materials—strengthens the plausibility of a causal interpretation.

We also note that the similarity of final "positive" shares (51–52%) does not contradict the significance of the intervention: what matters is not the terminal level but the trajectory of growth and the nature of change. In instructional assessment terms, visual artifacts serve as the "engine" of formative improvement: students repeatedly return to maps, correct arrows and mechanisms, and integrate data. We contend that such cycles are precisely how a new "grammar" of explanation is formed.

4.6. Limitations And Prospects for Scaling

We deliberately implemented the study in a "lightweight" configuration—without excessive technologization or complex statistical models—to assess the method's realism in an ordinary classroom. Correspondingly, there are limitations: lack of randomization, limited duration (five lessons), and a focus on qualitative indicators and simple distributions.

Future research will proceed along the following lines:

(i) extending the duration of the intervention and broadening the thematic spectrum (climate, matter cycles, energy, population dynamics),

(ii) Employing independent samples and teachers to assess the robustness of effects,

(iii) Refining metrics of the "qualitative grammar" of maps (e.g., number of mechanisms, moderator density, share of correct feedback loops),

(iv) Introducing minimal quantitative calibration of influences (without overburdening with formalism) to link causal pictures to basic data and elements of functional dependence.

Taken together, our results show that treating visualization of cause–effect relationships as a language of instructional reasoning leads to systematic improvements in explanation quality and to a more pronounced increase in "positive" outcomes compared with traditional practice, as well as to a motivational boost driven by practice-oriented scenarios. We believe this aligns with cognitive theories of multimodal encoding and external representations and supports the methodological hypothesis: it is not that "pictures increase interest" but rather that the language of visual causality restructures thinking activity and, consequently, learning outcomes.

5. DISCUSSION

Our study began from a simple yet methodologically fertile intuition: in school science, the visualization of cause–effect relationships is not a decorative "add-on" to content but a language of scientific reasoning in its own right—one that enables students (and teachers) to translate observations and facts into models, models into predictions, and predictions into justified decisions. To the extent that school science aspires to be practice oriented, this is precisely the language that should be placed at the center of classroom activity. It reduces extraneous cognitive load, structures attention, and renders assumptions and mechanisms explicit, thereby turning "understanding" from a metaphor into an operational procedure that lends itself to collective scrutiny and improvement. This, we believe, is the crucial point.

The empirical component of our work—a quasiexperiment in two parallel sixth-grade classes—confirmed that the systematic introduction of a visual "grammar of causality" leads not only to quantitative gains but also to a qualitative reconfiguration of explanatory thinking. At the aggregate level, we observed a more pronounced positive dynamic in the experimental group (an increase of 9.5 percentage points in the share of "positive" levels, versus 3.5 p.p. in the control group), as well as a characteristic shift in the distribution due to a reduction in low-level performance. In other words, the intervention is most effective precisely where reasoning had previously been hampered by fragmentation, confusion of correlation with causation, and the absence of explicit mechanisms. These conclusions are grounded in posttest evidence and pre–post comparisons and corroborate our methodological hypothesis regarding visualization as the "engine" of formative improvement.

Equally important, however, is that the primary effect cannot be captured by numbers alone: analysis of student maps and mini-defenses revealed a robust emergence of intermediate mechanisms, moderators, and feedback loops—that is, a shift from the linear "A–B" chain toward nascent systemic causal thinking. Without this configuration, the aspiration to practice-oriented science remains largely rhetorical.

This aligns with cognitive theories of multimodal encoding and supports the adequacy of the proposed hypothesis.

Overall, the significance of visualization in our study is twofold. First, it serves as an ergonomic interface between content and thought. By offloading working memory, it frees resources for constructing mechanisms, testing alternatives, and "stitching" diagrammatic arrows to data. Second, it functions as a social mediator of learning activity in the collaborative construction, cross-checking, and revision of maps, where every arrow and node becomes a topic of negotiated meaning—which we interpret as the "grammar of causality" within a culturally situated mode of student thinking.

Equally pedagogically salient is the motivational effect we observed. Task configurations such as "What will happen if…?," "Why did X intensify here?," and "Which measures would reduce…?," combined with obligatory causal mapping, establish a situation of intellectual choice with visible consequences. Among these parameters, "interest" ceases to be accidental and becomes a property of the learning practice itself. The increase in the proportion of students with high levels of activity and engagement in the experimental group—in contrast with modest changes in the control group—provides another indicator that the language of visual causality possesses its own motivational resource, making thought tangible, tractable, and productive for action.

Naturally, our work has several limitations. A quasiexperimental design cannot fully eliminate potential teacher, class-composition, or local-context effects. The duration of the formative stage (five lessons) precludes claims about effect saturation or long-term stability. Although our metrics are consistent with the logic of formative assessment, they remain largely qualitative–structural and call for further quantitative calibration.

The very "lightweight configuration" we adopted demonstrates the approach's principal practical strength: the method is realistic for an ordinary classroom and does not require costly technologization. In this sense, a well-designed diagrammatic grammar, clear procedures for collaborative construction, and a minimal corpus of data/graphs for model alignment suffice.

The practical implications follow directly from the theory and empirical findings. We recommend that science teachers treat visual causal maps as a throughline instrument of the course: from introducing concepts to explaining phenomena, from explanation to prediction, and from prediction to designing interventions and evaluating their consequences.

Methodologically, this entails the following:

1. an explicit "diagram grammar" (arrow direction, labeling of mechanisms, moderators, and feedback loops; a ban on "correlational" arrows without mechanisms),
2. cycles of revision and peer review to ensure that the map becomes a channel for argumentation rather than a static picture,
3. Regular "stitching" of the map to data (tables and graphs) as a procedure for plausibility checks.

At the level of education policy, the pursuit of practice orientation should be operationalized by integrating visual causal representation into standards, textbooks, and assessment systems so that students are expected not only to "know definitions" and "solve problems" but also to construct, defend, and refine causal models in a language accessible to sixth graders.

Finally, the study outlines a forward agenda. Theoretically, this involves developing scales for the "qualitative grammar" of student maps (mechanism density, share of correct moderators, configurations of feedback loops, resilience to common cognitive pitfalls). This suggests transferring the methodology to related subjects (biology, geography, physics) and educational levels. In terms of evaluation, it implies linking visual diagnostics with quasiquantitative calibration of influences (without excessive formalism) and benchmarking against external indicators of scientific literacy.

We proceed from the premise that the visualization of causality is not a "technique" but rather a form of scientific rationality accessible to schoolchildren. Once it becomes embedded in everyday classroom practice, natural phenomena begin to "speak" the language of mechanisms and conditions, and learning acquires a clear trajectory: from observation to model, from model to action, and from action to evaluation and a new cycle of refinement.

This, in essence, is the main outcome: we have demonstrated and substantiated the pedagogical productivity of visual causality as a means of cultivating practice-oriented thinking—productivity that is measurable in diagnostic results, visible in the evolution of explanations, and theoretically warranted. The results of the pedagogical experiment convincingly confirm the working hypothesis (H1) and refute the null hypothesis (H0). Integrating causal visualization into science instruction produced a marked educational effect, manifested in changes in the nature of students' reasoning, the structure of their explanations, and their level of cognitive awareness.

In particular, the students in the experimental group learned to construct more elaborate and logically coherent causal chains, to identify conditions and moderators, to ground their conclusions in the data, and to apply their knowledge in new contexts. Unlike the control group, where linear and descriptive explanations predominated, the experimental group demonstrated a shift toward systemic and predictive thinking—evidence of the emergence of genuinely practice-oriented reasoning.

Accordingly, we conclude that the visualization of cause–effect relationships is an effective didactic means of developing students' practice-oriented thinking and improves performance on all key rubric criteria: causality, coherence, identification of conditions, intervention analysis, and evidence-based interpretation of data. Our results have both theoretical and practical significance, underscoring the promise of embedding visual models of causality into the content and methods of the natural science curriculum.

On the basis of these findings, we propose a generalized architecture of causality (Figure 1), which reflects a synthesis of context, visualization, and the cognitive mechanisms that underwrite the development of practice-oriented thinking.

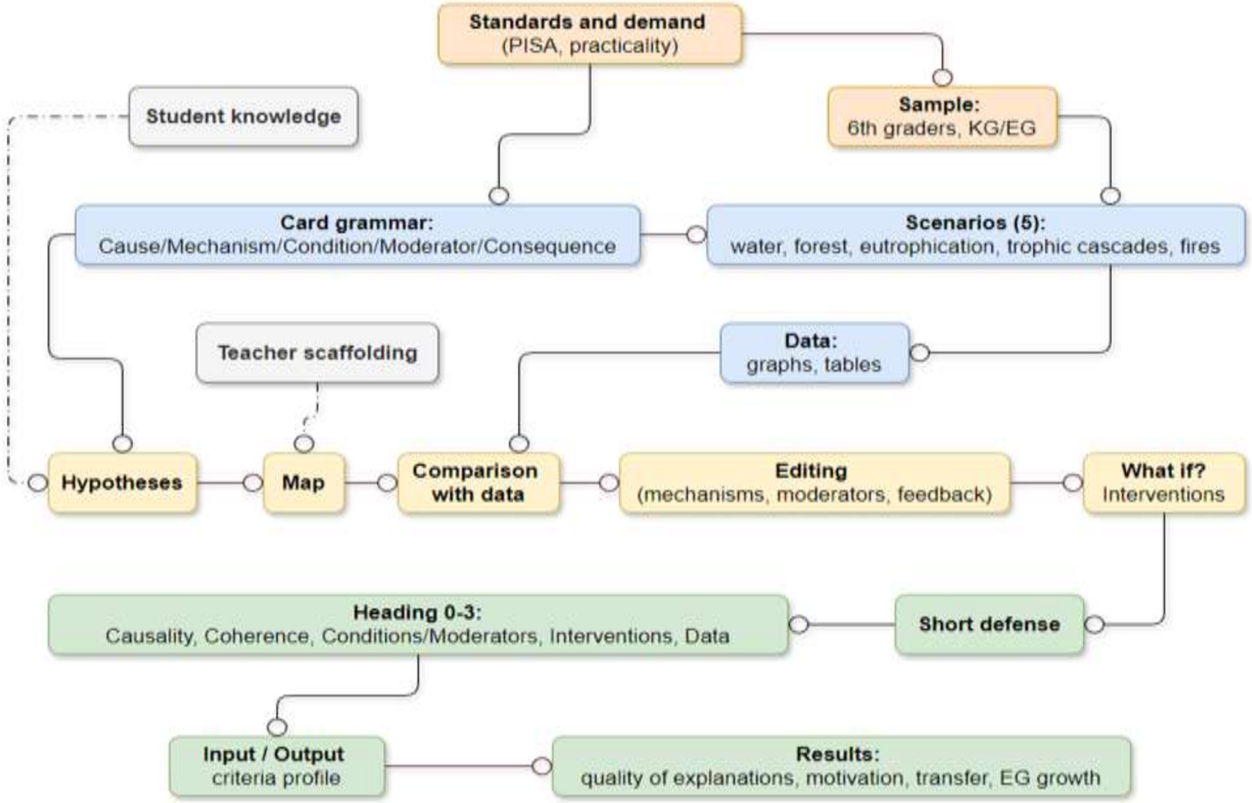

Figure 1: Conceptual Architecture of Cause–Effect Relationships (Dashed Lines Indicate Moderators and Feedback Loops).

The dashed lines in Figure 1 represent conditions and moderators (prior knowledge, scaffolding, individual differences), whereas the closed loops denote feedback from outcomes to scenarios and instructional methods.

Figure 1 presents a conceptual architecture of the causal relationships identified and tested in the study. It integrates four levels of pedagogical causality:

1. Context as normative and educational frames (PISA, national standards), sample characteristics, and students' prior knowledge—external causes that create the need for practice-oriented thinking;
2. Visualization as intervention—the principal transformation mechanism. Here, we specify the grammar of causal maps, lesson scenarios,

and instructional data; the teacher acts as moderator and catalyst of cognitive processes,

3. Lesson cycle as an internal causal loop: from hypotheses and the first map to revision, data analysis, and argumentation. This cycle embodies the didactic dynamic hypothesis - model - test - reflection.
4. Assessment and outcomes as a feedback system. The rubric, profiling, and analytics function as the mechanism of instructional self-organization, driving improvements in explanatory quality, motivation, and knowledge transfer.

This architecture performs both synthetic and prognostic functions: it condenses the empirical results into a coherent model of pedagogical causality.

Visualization emerges not only as a classroom tool but also as a mediator between context and thinking and between empirical facts and cognitive reconstruction. In this way, our model renders visible the hidden linkages across levels of educational influence—from standards to individual outcomes.

The language of systems analysis involves a shift from linear teaching to recursive learning, where each element is both cause and effect: data shape thinking, and thinking reshapes the perception of data.

The architecture can serve as a foundation for future lesson design and for developing digital tools that support the visualization of causal models.

6. CONCLUSION

Our study confirmed the initial hypothesis that the systematic visualization of cause–effect relationships is an effective instrument for developing students' practice-oriented thinking in the natural science curriculum. The experiment demonstrated that the use of visual causal models facilitates a transition from fragmented and linear explanations to systemic, substantiated, and predictive reasoning, where students begin to recognize not only the immediate causes of phenomena but also the underlying conditions, mechanisms, moderators, and feedback loops.

The empirical findings revealed a clear positive dynamic in learning outcomes: the proportion of students achieving medium and high levels on the causal reasoning rubric increased significantly, whereas the share of low-level performance decreased. Importantly, the most notable progress occurred not among the highest achievers but within the group that had previously struggled to manage complex dependencies and distinguish correlation from causation. This confirms the effectiveness of the methodology as a means of cognitive support and educational equalization.

A qualitative analysis of students' causal maps and brief oral defenses revealed the emergence of a more complex "grammar of explanation." Students began to introduce intermediate mechanisms, distinguish between conditions and effects, incorporate moderators, and construct simple feedback loops. In this sense, visualization became not an illustration but a language of reasoning - a medium for externalizing and reflecting upon the cognitive process.

Theoretically, our results are consistent with contemporary cognitive models of multimodal encoding and the theory of external representations. Visual artifacts reduce the extraneous load on working memory, structure attention, and define possible reasoning trajectories. Practically, this translates into more coherent and evidence-based explanations, as well as a noticeable rise in motivation and engagement.

The methodology implemented in our study has demonstrated its feasibility within the framework of ordinary classroom practice without the need for complex technological tools. It requires only that the teacher master basic principles of "diagrammatic grammar" and be willing to use the causal map not as a static outcome but as an instrument of reflection, dialog, and self-assessment.

Thus, the visualization of cause–effect relationships emerge as a pedagogical technology of a new type - a means of forming systemic, argumentatively grounded, and practice-oriented thinking. Its implementation not only increases the cognitive meaningfulness of scientific phenomena but also brings school science closer to the genuine culture of scientific reasoning, where the learner becomes not a passive consumer of knowledge but an active constructor of meaning.

The results of our research open perspectives for further development of this approach - its extension to other subject domains, the creation of digital tools for causal visualization, and the design of quantitative metrics for evaluating the structure of causal maps. Ultimately, the visual language of causality may become a universal mediator between data and thought and between observation and action, thus forming the core of contemporary scientific education.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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