Roots & Migrants: a user-centered design of an interactive mapping platform for teaching and learning historical population dynamics in the U.S.

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ABSTRACT

Interactive maps offer a powerful way to represent spatiotemporal processes such as population change by linking events across space and time but designing them for education requires balancing exploration with curriculum goals, addressing challenges of interpretation arising from uneven data coverage, and accommodating constraints such as limited instructional time and map literacy. Because many existing tools are not built around classroom workflows, they may fail to sustain inquiry or support effective instruction. This article shows how a user-centered design (UCD) approach can improve educational mapping through the collaborative development of Roots & Migrants, a web-based map platform for teaching and learning about U.S. historical population dynamics. We implemented UCD through two participatory workshops with high school teachers and students, using feedback to iteratively design the system, and co-develop classroom lesson activities, drawing on collaborative geovisualization to support spatial knowl-edge construction. The study identifies cartographic representation and interaction strategies that support spatiotemporal inquiry for novice map users. It also shows how interface and content design can help students interpret population maps as partial historical records shaped by uneven data coverage. Findings further suggest that students benefit from opportunities for open exploration rather than strictly linear storytelling when exploration anchored to specific inquiry tasks and classroom workflows. We argue that educational interactive maps should be designed as instruc-tional systems grounded in classroom practice, pedagogical goals, and data limitations, with implications beyond history education.

Introduction

Interactive maps offer a powerful way to represent spatiotemporal processes such as population change by connecting where events occur, when they unfold, and how they relate. By integrating narrative elements with spatiotemporal data, they support exploration of what happens, where, and when, all within a narrative context (Andrienko et al., 2003; Peuquet, 2002; Roth, 2021). Designing interactive mapping tools for learning, however, requires balancing narrative support with analytic interactivity so that users can both follow an exploratory storyline and actively compare patterns across time, space and related variables. In classrooms, this design challenge must also accommodate curriculum goals, potential misinterpretation arising from uneven data coverage, and practical constraints such as limited instructional time and map literacy. These considerations are especially important in history where historical reasoning depends on linking events to place and time and interpreting multivariate drivers including demographic, political, economic, and environmental conditions.

Yet in practice, many teachers rely on relatively simple, browser-based mapping tools such as Google Voyager, ArcGIS Online and StoryMaps, and publicly accessible story maps that are free at point of use. Examples include "The Atlantic Slave Trade in Two Minutes" (Khan & Bouie, 2021), redlining maps digitized by the Mapping Inequality project (Nelson et al., 2018), National Archives educational materials on DocsTeach (National Archives, 2026), digital collections from the Library of Congress (Library of Congress, 2026) as well as static historical maps in digital or print form. These resources are widely used because they are accessible and quick to adopt; however, they are rarely designed to support learning activities and core spatiotemporal tasks such as identifying patterns, comparing across time, and interpreting change (Andrienko et al., 2003). Although we use history as a motivating domain, this gap reflects a broader design challenge in educational interactive mapping.

Many educational story map implementations prioritize narrative coherence and immediate comprehension, but this emphasis can constrain inquiry by steering students

through a largely linear sequence with limited opportunities to pose their own questions or test alternative explanations (Mayer et al., 2023). When complex historical topics require multiple places, periods, and explanatory variables, students must mentally align scales, time steps, and variables across maps, which weakens continuity and makes spatiotemporal interpretation difficult (Bodemer & Faust, 2006; Bodemer & Ploetzner, 2004). Although some tools include features for comparing across space, time, and variables, they are not consistently designed to support classroom inquiry. Comparison is often left implicit rather than structured in ways that guide students' analysis.

A gap therefore remains between technical development and instructional practice: Many educators often lack the time and technical expertise to design, customize and use advanced interactive tools (Hong, 2016), while designers and developers may not fully account for instructional constraints, classroom pacing, and learning goals when designing systems (Shin, 2006, as cited in Artvinli, 2010; Hong, 2016). As a result, general-purpose tools are frequently repurposed into educational settings, with instructional practice expected to accommodate the tool rather than the tool being designed for instructional needs (National Research Council, 2006). Bridging this divide requires design processes that engage teachers and students as co-designers, ensuring that instructional goals and classroom constraints directly inform interaction and interface decisions, using a collaborative geovisualization approach to designing educational maps.

To address these challenges, we adopt a user-centered design (UCD) approach that engages interdependent users so that multiple perspectives shape tool development. In this study, we apply UCD to develop Roots & Migrants, an interactive mapping platform designed to support inquiry-based learning about U.S. historical population dynamics. The work is motivated in part by representativeness limits in historical quantitative records, including uneven coverage across groups and places and changing census classifications (e.g. race) over time, which can constrain what population maps make visible. We situate the study in U.S. high school history education, where students must interpret population change across multiple places, time periods, and explanatory factors.

This paper reports the UCD process, the resulting design outcomes and implications for educational spatiotemporal mapping, using Roots & Migrants and U.S. high school history classrooms as the primary case study. We show how the platform consolidates data, maps, and instructional materials into a single environment and supports inquiry-based lesson plans that teachers can adopt in classroom instruction. This paper makes three contributions. First, we identify representation and interaction strategies that support core classroom spatiotemporal tasks, including temporal comparison and coordinated exploration across views to enable evidence-based interpretation. Second, we demonstrate how engaging interdependent teacher–student users translates classroom workflows, instructional constraints, and learning goals into concrete, reusable design requirements for educational mapping tools. Third, we show how design choices can reveal and contextualize uneven historical data coverage, helping students interpret what population maps show, and what they omit, especially for underrepresented groups.

The remainder of this paper presents related work that summarizes prior research on spatiotemporal learning, narrative mapping, and user-centered design, then describes our UCD methodology and workshops, reports the Roots & Migrants system and co-designed lesson activities, and concludes with design implications and future work.

Related work

This section situates our study within three areas: (1) current strategies and practices for incorporating UCD into the creation of interactive mapping tools, (2) narrative support and interactivity, (3) spatiotemporal representation and instructional constraints. Across these strands, we emphasize a shared classroom design problem: supporting explicit spatiotemporal comparison and evidence-based interpretation for novice map users under time constraints, while reducing misinterpretation that can arise from uneven historical data coverage. This framing motivates our UCD approach and the design requirements implemented in Roots & Migrants. Finally, we discuss how integrating user-centered design with interactive maps can address current challenges in tool design and pedagogy, forming the theoretical foundation for our study.

User-centered design in geovisualization

User-centered design (UCD) prioritizes users' needs throughout the development of geovisualization tools (T. A. Slocum et al., 2001). Successful UCD requires early user involvement to prevent implementation problems and account for diverse user profiles (Bhowmick et al., 2008; T. Slocum et al., 2003), employing methodologies including focus groups, purposeful sampling, and expert-based, theory-based, or user-based evaluation (Robinson et al., 2005; Roth et al., 2015).

Most UCD applications in cartography and GIScience target independent user groups. For example,

Robinson et al. (2005) developed ESTAT for epidemiologists integrating multiple data visualization methods while Bhowmick et al. (2008) created the Pennsylvania Cancer Atlas for health researchers and spatial scientists. Even when educational maps are developed, UCD typically addresses teachers or students separately, failing to account for their interdependent relationship within classroom environments.

James et al. (2020) and Pagano et al. (2024a) demonstrate that research in GIS education typically optimizes curriculum and learning outcomes while adapting the GIS software, leaving limited guidance for UCD of a shared tool that must work for teachers and students as interdependent users. Hong (2017) proposed UCD for creating learning materials and introducing technology in classrooms, yet the focus remains on learning materials rather than geovisualization tools serving both teachers and students simultaneously.

However, these studies reveal an important limitation: their success depended on designing for users with independent roles and objectives. Roth et al. (2015), for example, developed GeoVISTA CrimeViz with feedback from investigators, officers, and administrators, identifying tensions among their differing needs. However, the system treats these groups as separate user profiles rather than interdependent co-users engaged in shared work through the same tool. This limitation highlights the need for design frameworks that support shared interaction and collaborative use of geovisualization tools among multiple users (Fuhrmann & Pike, 2005).

Educational maps present a unique challenge: teachers need curriculum alignment and support for inquiry-based activities, while students need exploration and engagement. These needs are interdependent because teacher choices shape how students understand spatial information, while student interactions reveal effective pedagogical approaches.

This study demonstrates principles for applying UCD with interdependent user groups, specifically teachers and students in high school. Through collaborative workshops, focus groups, purposeful sampling, and user-based evaluation, we show how UCD must account for both individual needs and relational dynamics to create effective educational geovisualization tools. Accordingly, educational interactive maps should be designed as instructional systems: tool + tasks + supports, co-developed with teachers and students to fit classroom workflows.

Narrative support and interactivity

Narrative structures help users build mental models of how spatiotemporal phenomena unfold and relate, reducing interpretive burden (Mayr & Windhager, 2018). Aside from limiting exploration, linearity becomes an interpretative risk when quantitative data has uneven coverage: readers may incorrectly treat missing data as absence unless made explicit.

Narrative frameworks have been applied through various storytelling formats in cartography. Roth (2021) characterizes storytelling formats based on linearity, where guided narrative control fixes the sequence of interpretation and limits users' ability to explore data independently. Buckley and Case (2025), and Prestby (2025) note that these omissions, framing, and design choices are ethical issues because they shape interpretation and may cause distrust.

Research shows that narrative-driven maps can benefit specific audiences, but outcomes vary by design. Design choices of narrative-driven maps affect what people can understand and remember, while topic and users' beliefs mainly affect how they feel (Roth, 2021; Song et al., 2022) and that users with lower map literacy may prefer structured formats such as scrollytelling or guided animations. Lan et al. (2022) further notes that interactivity can help move from data to narratives by allowing users to extract insights from diverse indicators, yet this requires careful handling of incomplete datasets.

Biriukov (2021), however, reclassifies storytelling maps as scroll-driven, dynamic-interactive, path-visualization, and complex-story forms, supporting designs where users can gain insight from evidence (including data coverage gaps and uncertainty) rather than being guided through a single authored path. However, Roth (2021) and Biriukov (2021) are less explicit about the instructional framework needed when students are given freedom to navigate an interactive map.

Spatio-temporal maps and instructional constraints

Spatiotemporal maps employ common techniques including coordinated views, animations, superimposition, juxtaposition, and space–time visualization that support powerful analysis of change over time but, novice users tend to interpret complex maps less efficiently than experts, as reflected in longer fixation patterns during map reading (Mayr & Windhager, 2018; Ooms et al., 2012). Among these techniques, animation has received particular attention in cartographic research due to its potentials and drawbacks; animation can effectively represent change but overwhelms viewers when poorly designed (Harrower & Fabrikant, 2008; Kraak, 2007), produce change blindness with rapid temporal displays (Fish et al., 2011), and comparison across multiple views that may increase cognitive load (Munzner, 2014).

National assessments confirm map interpretation and comparison tasks are consistently difficult across grades 4, 8 and 12 (Bednarz et al., 2006), who often revert to fragile reasoning strategies such as guessing or prior beliefs (Pagano et al., 2024b). This pattern suggests that spatiotemporal complexity becomes an instructional problem in classrooms. This is especially consequential when students are expected to justify explanations through comparison across time, place, and contextual variables within class periods. The pedagogical implications of these techniques, how they should be designed to support inquiry and reasoning in time-constrained classrooms, are less clearly specified, especially where students must integrate location, attributes, and time. For example, HisVA, an interactive visual analytics tool for exploring historical events, supports exploration of Wikipedia-derived historical events through coordinated event, map, and resource views; it was evaluated with undergraduate students in a university history course in a flipped-classroom environment (Han et al., 2022). Although powerful, such workflows require sustained interaction, filtering, and synthesis; demands that may be difficult to support in many high school classrooms without extended guidance and class time.

Bednarz's et al. (2006) call for inquiry-based learning in geography could be supported through spatiotemporal techniques yet guidance on designing them for instruction and addressing their issues remains limited. These findings suggest that classroom tools should externalize comparison workflows, so students spend less effort decoding and more effort reasoning. We address these challenges in the design outcome section later in this paper.

Methods: user-centered design process of roots & migrants

We conducted a case study in U.S. high school history education to examine how interactive maps can support inquiry-based learning about historical population dynamics.

Our approach adapts from existing UCD frameworks (Bhowmick et al., 2008; Robinson et al., 2005; Roth, 2013; Hong, 2017) and follows five iterative stages (Figure 1): (1) Work domain analysis (2) Conceptual development (3) App design and implementation (4) Lesson plan development (5) Evaluation including pre-alpha (preliminary sketches) and post-alpha (lesson-based) reviews, supplemented by external evaluation conducted by the Center for Evaluation and Assessments (CEA).

These sections below describe each stage and summarize insights from teachers and students. We analyzed responses using thematic analysis guided by predefined questions to identify recurring patterns and themes.

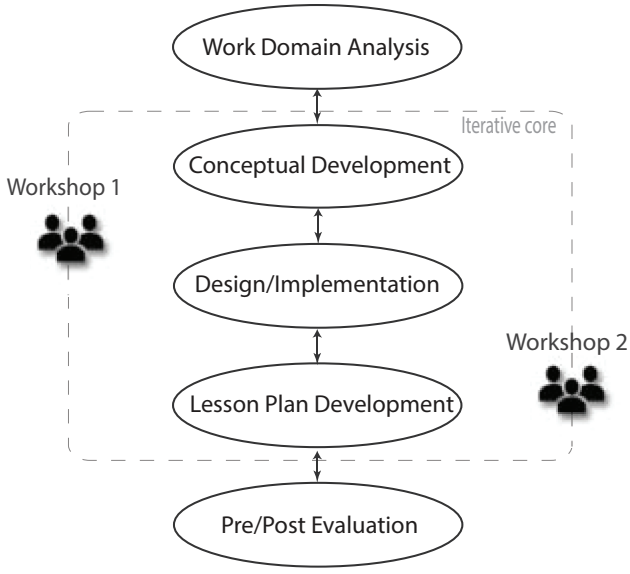


Figure 1. User-centered design framework used for developing Roots & Migrants, showing the iterative process from work domain analysis to lesson plan development.

Work domain analysis

Participants and recruitment

Our work domain analysis focused on understanding needs and constraints in teaching U.S. history and population dynamics. Some participants attended more than one workshop; counts below are reported collectively.

(1) Teachers ($n = 10$): Teachers from six Iowa high schools who teach Advanced Placement U.S History (APUSH) and/or Advanced Placement Human Geography (APHG) participated. We used AP courses to ensure shared curricular baseline and because these courses regularly cover migration, population change, and related concepts within standardized leaning objectives.
(2) High school students ($n = 6$): Students in grades 10–11 participated through a summer internship program (two from California, one each from Virginia and Washington, and two international students). Because this was an early-stage design effort, we kept the student group small to support in-depth discussion and rapid iteration; this group is treated as formative input rather than a representative classroom sample.
(3) Undergraduate and graduate students: One undergraduate and three graduate students with a background in geography and geographic information science (GIScience) participated to support prototyping and technical translation during workshops.

During the initial workshop (Workshop 1), teachers discussed key curriculum topics, teaching strategies, classroom resources and identified content requirements with reference to the IowaCore (2022) and the AP curriculum.

Focus group procedures

Focus group questions were organized around 7 themes: curriculum needs, student engagement, interactive tools and resources, resource gaps, classroom support, flexibility, and student feedback (Table 1). Data were captured through written notes, audio recordings, and post-workshop surveys. We analyzed transcripts and notes using thematic analysis. We began with a deductive structure aligned to the focus group themes and added subthemes as needed to capture recurring patterns, constraints, and design requirements. Findings were summarized as design requirements that informed subsequent stages.

Representativeness and historical data limitations

A central motivation for Roots & Migrants is the well-documented underrepresentation and misrepresentation of some populations (e.g. Native Americans, Black and Hispanic Populations) in historical census records, administrative sources, and crowd-sourced family tree data (Koylu & Kasakoff, 2025). These limitations shaped the initial framing of the project and positioned representativeness as both an analytical and educational concern.

Conceptual development & design goal

During conceptual development, we introduced early-stage sketches of Roots and Migrants (Nwajiaku & Koylu, 2024) to collect feedback on concepts and interactions. The prototype used placeholder data and minimally styled map elements to keep attention on concepts and interactions rather than interface design. Participants first received a brief overview and then explored the sketches freely for approximately 50 minutes. This was followed by a short, guided walkthrough with example tasks (e.g. using a time control to examine change across decades). Participants were explicitly told the prototype was incomplete and were asked to identify usability issues and suggest improvements. We introduced early-stage sketches alongside the work domain analysis (rather than strictly after it) to encourage open critique and reduce the likelihood that participants would evaluate the system as a finished product.

Pre-alpha evaluation

The pre-alpha evaluation was conducted within Workshop 1 activities. Teachers and students reviewed the early-stage prototype, discussed functional needs, and commented on interface elements and interactivity. The goal was to identify requirements and potential usability issues before developing the alpha version. At this stage, the CEA collected feedback on workshop feasibility and clarity using structured Qualtrics surveys.

Alpha development and iterative refinement

Based on requirements from the work domain analysis and pre-alpha feedback, we developed an alpha prototype of Roots & Migrants and iteratively refined it through additional user feedback. The alpha implementation focused on supporting spatiotemporal exploration and comparison aligned with classroom needs. (Detailed interface features and design choices are reported in the Design Outcomes section.)

Lesson plan development

During the second workshop, teachers were divided into two focus groups and used the Roots & Migrants Alpha version to develop lesson plans. We provided sample lesson plans that teachers could modify. Teachers took different approaches: some modified the provided templates, some created

Table 1. Focus group discussion questions (1st workshop).

Themes	Focus group questions
Curriculum needs	• What are the key topics you currently cover in your curriculum related to migration and historical events? • How do you design this part of the curriculum? (schedule, lesson structure, resources, assessment methods)
Student Engagement	How do you currently engage students in learning about migration history?
Interactive Tools and Resources	• What types of interactive tools or resources would be most beneficial for your teaching? • What types of data visualizations would be most effective in conveying migration patterns? • If you have used web-based maps for your teaching, please share some experiences.
Resource Gaps	Are there specific areas where you feel your current resources are lacking?
Classroom Support	• How could the Roots & Migrants application support teaching and learning in your classroom? • What specific functionalities or features would best support your teaching needs? • How can the application facilitate student engagement and interactive learning?
Flexibility	To what degree do you want flexibility in using the Roots & Migrants application?
Student Feedback and support	• How can we incorporate student feedback and input into the application design? • What support or training would you need to effectively use this application in your classroom?

Table 2. Focus group discussion questions (2nd workshop).

Themes	Focus group questions
Teaching U.S history	What aspects of teaching U.S history or migration do you find most difficult to convey to students?
	Did the workshop challenge or expand your perspective on how migration is taught, or how you use visual tools like interactive maps?
Student Needs	What features or approaches in Roots & Migrants do you think would resonate with students? Why?
Co-design Process	What did you find most surprising about co-designing curriculum with students or colleagues?
Classroom integration	Looking ahead, what would make you feel more confident using a tool like Roots & Migrants in your classroom?
	If you were to teach with Roots & Migrants next week, what is the first thing you would change or add to make it work for your class?

entirely new lesson plans independently, and others collaborated with one or two additional teachers within their focus groups to design activities integrating the tool's features for teaching historical population dynamics. Meanwhile, students remained in these focus groups to independently evaluate the Alpha version. Following these focus group activities, we conducted a discussion using questions organized around 5 themes: teaching U.S. history, student needs, co-design process and classroom integration (see Table 2).

Post-alpha evaluation

During the post-alpha phase, teachers and students explored the interface independently at their own pace, with developers available to assist with technical issues. After the session, participants completed a qualitative Qualtrics survey about workshop effectiveness, interface features, and potential classroom applications. The CEA evaluator also documented teachers' plans for incorporating the tool into their lessons. These sessions were not formal assessments of usability metrics or learning outcomes, but rather informal evaluations intended to guide iterative design decisions and identify areas for refinement.

Results

Workshop findings and formative evaluation

Workshop 1 (work domain analysis and pre-alpha)

Workshop discussions highlighted how teachers adapt curricula in practice. Teachers described revising topics each year, adjusting emphasis based on current events, and selecting materials that fit limited class time. Both teachers and students agreed that maps support learning in class, but they emphasized that many existing mapping tools are difficult to use in everyday classroom settings. Printed maps were seen as less effective for communicating change over time, and teachers reported supplementing instruction with videos to increase engagement. We identified five key constraints that shape how interactive maps can be adopted in classrooms:

(1) Device compatibility: Classroom technology varies (e.g. iPad, Chromebook), which increases the need for browser-based tools that work across platforms and do not require installation.
(2) Time constraints: Teachers prefer tools that are ready to use during instruction, with minimal setup and limited need for training.
(3) Student map literacy: Students often struggle with foundational map concepts (e.g. scale), and both teachers and students noted difficulty interpreting specialized spatial measures (e.g. migration metrics).
(4) Curriculum alignment: Tools are less likely to be used when they are not paired with lesson-ready materials aligned to instructional goals.
(5) Tool complexity: Many GIS and mapping products are perceived as too complex for daily classroom use.

To identify early requirement, teachers and students reviewed an early-stage prototype (see Figure 2). Figure 2 illustrate the early-stage sketch of the population module, including basic map elements and a time slider and a story panel. Additional early-stage sketches are provided in Appendix Figure A.1, A.2. Participants used these sketches to comment on clarity, interaction needs, and content expectations.

We categorize the feedback into four requirements: usability, content support, student engagement, and flexibility, which are summarized in Table 3. Usability was emphasized as essential for classroom adoption, including a clear time control and intuitive navigation that teachers could use confidently without extensive training. Content support requirements focused on covering core U.S. history topics linked to population change and connecting map patterns to explanatory drivers such as policy, race/ethnicity, labor, settlement, and infrastructure. Teachers specifically requested coverage of major migration events, including the Great Migration, Trail of Tears, Gold

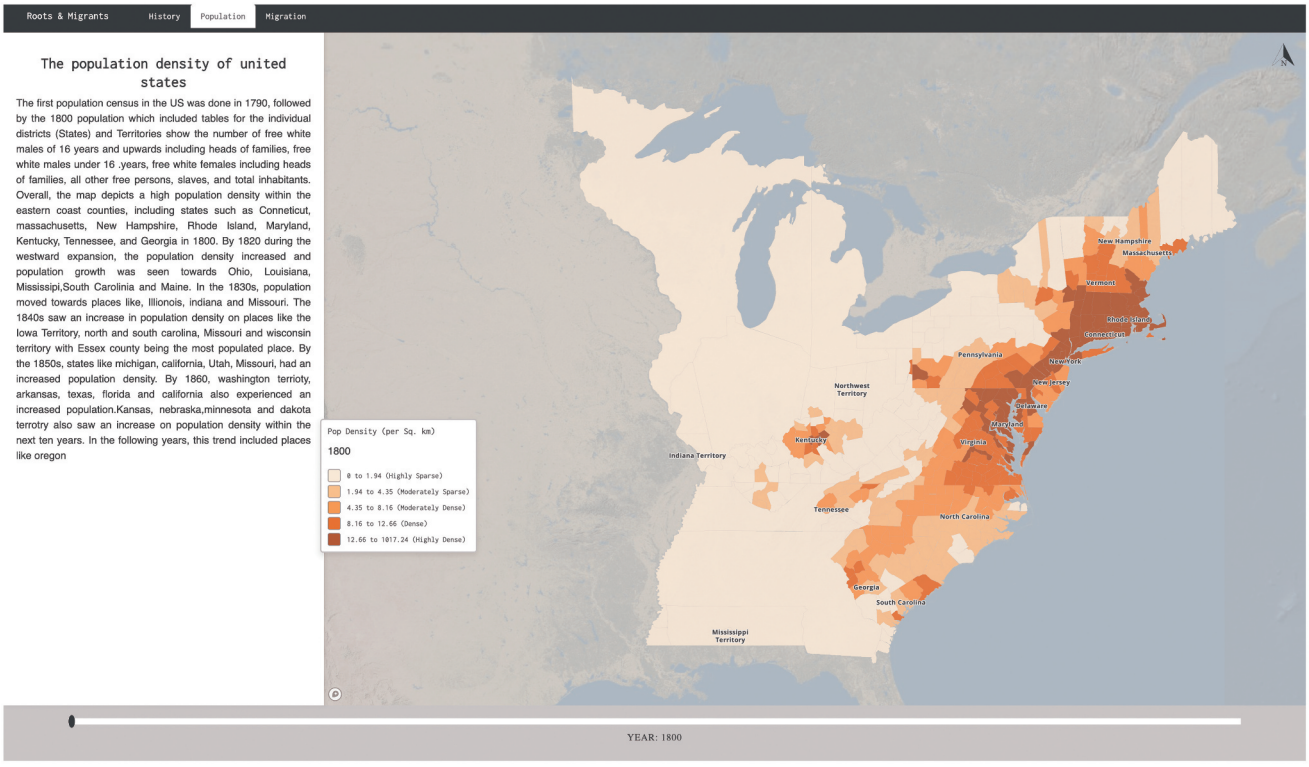


Figure 2. Early sketch of the population density interface.

Rush, and industrialization, along with relevant laws, population flows, and settlement patterns. Student engagement requirements emphasized concise presentation, multimedia support, and interaction patterns that help students explore without being overwhelmed. Flexibility requirements reflected variation in teacher preferences: some wanted ready-to-use lessons, while others wanted the ability to customize layers, scales, and questions for different class contexts.

Table 3. Initial requirements.

Initial requirements	
Qualitative and Quantitative Content & Data	Inclusion of the following events and data: • Acts and Laws such as Indian Removal act, Dawes Act, Homestead Act. • Age and Race related population density, migration flows. • Layers such as Railway system, Free and Slave states. • Events such as Great migration, Trail of tears. Oregon fever, Westward expansion, Mexican American war, Indian war, California gold rush, Mormon trail. • Contemporary census data. • Electoral college maps. • Maps of ruling political parties by state. • County-to-county migration. • Streamline narrative texts. • Images, avatars and historical photos.
Topics on Migration	Types of migration, factors influencing migration, reasons for migration, industrialization, urbanization.
Interactivity and design	• Ability to display maps side by side. • User-friendly time slider. • Interactive map features for specific events. • Event timeline to be consistent and divided into major historic events in progression. • Ability to toggle the units on legends. • Ability to change geographic scale. • Include a tutorial video. • Ability to support critical thinking questions. • Show major events as annotations.
Map elements	• Compass. • Scale. • Consistent legend design.
Terminologies	Accessible terms and concepts.

Workshop 2 (post-alpha)

In the second workshop and follow-up post-alpha sessions, teachers and students evaluated the alpha system and discussed how it could be used in classroom activities. Participants generally described the sessions as productive and reported learning new ways to approach spatiotemporal topics with maps. Teachers highlighted the benefits of being consulted early in the design process and valued the collaborative format for discussing how the tool could fit within instruction. In addition to iterative design, participants suggested improvements to workshop structure, including more hands-on time, fewer repetitive prompts, and involvement from a broader range of teaching backgrounds.

Teachers reported that the alpha system represented a clear improvement relative to the early-stage prototype, particularly in its ability to support exploration of change over time and comparison across views. They also noted ongoing instructional challenges that shape how the tool should be designed and used: (1) map and data literacy challenges, (2) teaching sensitive historical topics, and (3) grade-level suitability. Teachers observed that students often struggle with numeracy, graphical interpretation, and map reading, which affects how students interpret population data and derived measures. This reinforced the need for clearer explanations, accessible terminology, and interaction patterns that make comparisons straightforward. Teachers also noted that students are often more interested in stories than data, identifying the need to incentivize students toward map analysis. Second, teachers described topics involving minority history as difficult to teach because students may hesitate to ask questions in class. They viewed independent map exploration as a potential way for students to engage with sensitive content without social pressure. Third, participants suggested the tool would be most effective for grades seven and above, with clearer guidance needed for younger users.

Positive feedback focused on the tool's interactive affordances relative to static maps, especially temporal exploration and comparison. Teachers described the compare functionality as particularly engaging for classroom tasks and discussion. Several teachers also emphasized the importance of presenting diverse perspectives and noted that many current resources remain narrowly framed; they viewed the platform as an opportunity to broaden representation through content and narratives.

Design outcomes from the UCD process

The UCD process produced two linked outcomes: (1) classroom requirements for spatiotemporal inquiry and (2) representation and interaction decisions implemented in Roots & Migrants. Table 4 summarizes the specific implementations of these design decisions based on user requirements.

Roots & migrants alpha version (alpha version under development)

The alpha version of Roots & Migrants (Nwajiaku & Koylu, 2025) provided an integrated environment for exploring U.S. historical population dynamics through four thematic modules: History, Population, Migration, and Immigration. The alpha system was used in Workshop 2 for lesson activity co-design and in post-alpha sessions for formative feedback on classroom fit, interpretability, and interaction design.

Representativeness and historical data limitations

Historical census records, administrative sources, and crowd-sourced family tree datasets provide valuable data on population change and demographic history, but none offers complete or uniform coverage across groups, places, and time (Koylu & Kasakoff, 2025). Census data often undercount or misclassify populations, use changing racial categories, and record identities inconsistently. These problems are especially pronounced for Native Americans, who were sometimes counted through separate tribal rolls or excluded based on treaty status; for African Americans, whose records were shaped by slavery and later unequal

Table 4. Design decisions based on user feedback.

Requirement from workshops/evaluations	Design response in Roots & Migrants
Quick onboarding and support for novice users	Tutorial video and in-app help elements
Compare maps across time, themes, and places	Side-by-side Compare tool with optional synchronization and attribute table
Maintain narrative context while exploring maps	Dual-panel layout (map + context/story panel) with multimedia support (images, videos, documents)
Make temporal change explorable (not just shown once)	User-controlled time navigation; pause/play and looping options for tracking change
Add explanatory context without overloading the main map	Overlay controls to toggle contextual layers (territorial change, routes, infrastructure, demographic context)
Support interpretation of non-technical metrics	Metric explanation feature (definitions, formulas, and data notes) presented near the map
Handle missing data and uneven historical coverage	Data-availability messages, coverage notes, and disabled time steps for unavailable years
Connect map exploration to classroom assessment goals	Example questions aligned with Advanced Placement expectations
Preserve continuity during inquiry across modules	Persistent time selection when switching themes

documentation; and for Mexican American populations, whose racial classification shifted over time and was often recorded under broad categories such as white. Administrative records and other historical sources are similarly uneven because documentation practices, jurisdictional boundaries, and survival of archives vary widely over time and geography.

Family tree datasets contribute a different kind of evidence. Unlike the census, which is largely a decennial snapshot of residence and household structure, family trees provide longitudinal, person-centered linkages, connecting parents, spouses, children, and extended kin, often with dates and places of birth, marriage, and death. These kin links can reveal migration indirectly through life-course events (e.g. changes in children's birthplaces within a family) and allow reconstruction of extended kin networks that the census alone cannot reliably recover (Koylu & Kasakoff, 2022) At the same time, crowd-sourced trees have strong and uneven participation biases: some populations are sparsely represented because names were inconsistently recorded, key life events were not documented, records are difficult to access or interpret, and racial designations changed over time. As a result, Native American, Black, and Mexican populations are often underrepresented in tree data, and the magnitude of this bias varies across place and time.

Communicating representativeness and historical data limitations

Because historical datasets often contain missing data and uneven coverage, the system includes mechanisms to communicate limitations without disrupting inquiry. First, the application shows a message when data are not available for a selected year or area. Second, an info button next to the legend explains which years are available and notes on data limitations. Third, the time slider blocks or disables years with missing data preventing selection. These features are intended to reduce confusion and prevent misinterpretation driven by data gaps.

For Roots & Migrants, representativeness limits are not only analytical constraints but also design constraints. They motivated a platform that pairs quantitative maps with narrative materials, historical documents, and contextual storytelling, and that explicitly communicates coverage and uncertainty.

The goal is to help students interpret population change as evidence drawn from incomplete historical records, which helps learning both what the data make visible and what they leave out, while still supporting inquiry into spatiotemporal patterns and their historical drivers. For example, selecting the Indian Removal Act loads contextual resources in the story panel (historical images, videos, primary documents, and curated external links) with a spatial Trail of Tears layer. The history module also includes a persistent Native Lands layer beneath time-enabled U.S. boundaries, helping students see territorial expansion over Indigenous homelands. Together, these features support inquiry into underrepresented histories by adding evidence where quantitative records are uneven, without implying the mapped data alone provide a complete account.

Design iterations

Across workshops, the initial constraints and requirements were translated into concrete design responses in the alpha system. Rather than requiring learners to mentally integrate multiple disconnected maps, the alpha design emphasized coordinated exploration, explicit comparison, and reduced fragmentation through an integrated environment and structured supporting materials. Detailed system features and the requirement-to-design mapping are reported in Design Outcomes (Table 4). We report this iteration process below, describing what was implemented after Workshop 1 and how features were refined after Workshop 2.

Early designs risked overwhelming students with dense narrative texts and unsynchronized views, so we separated historical context into two segments. First, state-specific events were presented as interactive markers placed on the map, each opening a pop-up summary. Second, major events were presented on timelines while additional events remained optional through an overlay toggle (Figure 3). Figure 3 presents an annotated view of Roots & Migrants illustrating the history module. The story panel contains an event timeline of major events, with optional multimedia and external links, while the map displays geographic context through interactive pop-ups and layers. The overlay panel on the right allows additional content (e.g. Indigenous Lands) to be toggled on or off so users can add event context without cluttering the default view. Below the map, time slider and standard map controls such as zoom support exploring change over time.

As shown in Figure 3, the history module connects events across global and local scales through event-driven inquiry. When a student selects the "1861 American Civil War Begins" from the event timeline, the story panel opens with a brief narrative, images, an embedded animated video, and curated external resources. The map updates to the corresponding year, prompting the student to interpret the Civil War through place-specific events visible on the map. In this case, an event marker

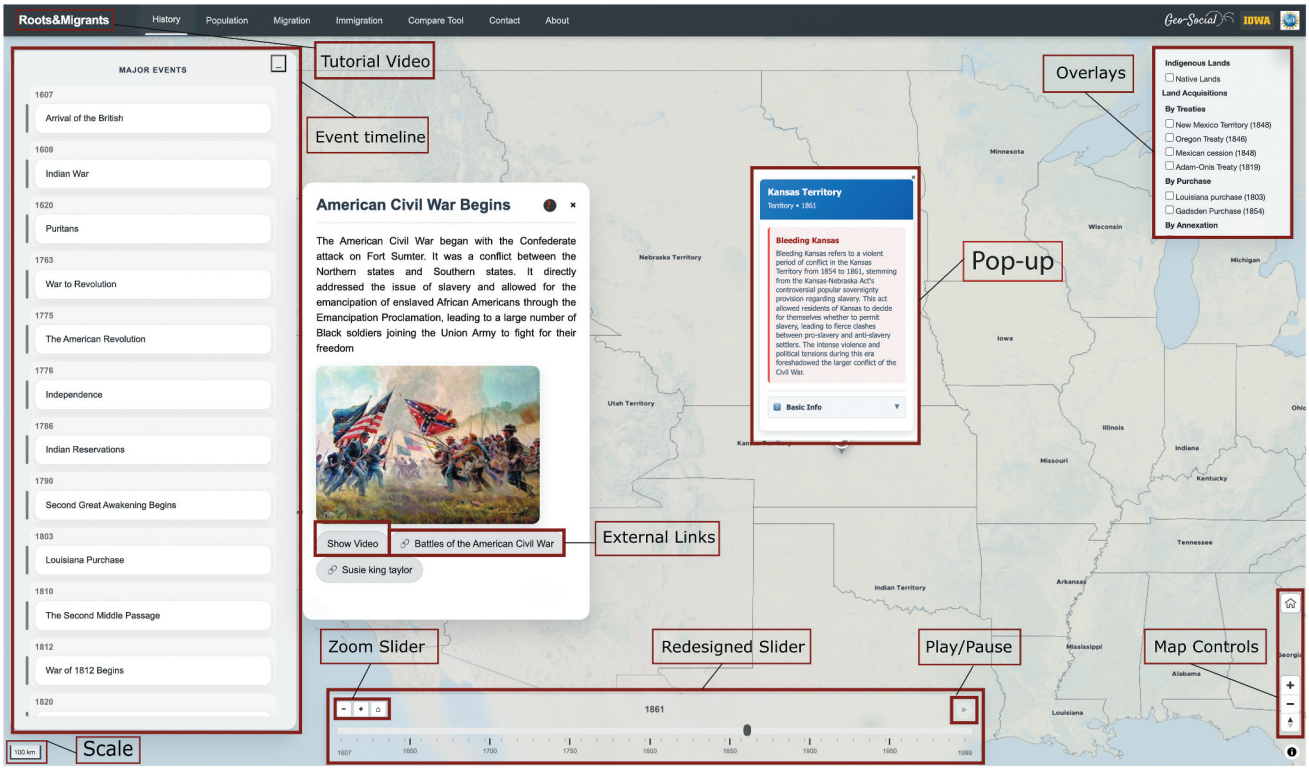


Figure 3. History tab interface displaying major events timeline, interactive map with pop-ups, and navigation controls.

appears in Kansas; selecting it opens a pop-up describing Bleeding Kansas. With the Civil War narrative still visible, the student can interpret Bleeding Kansas as a "tragic prelude" to the Civil War, linking a local conflict to a broader national event.

Teachers noted that the migration measure was difficult to interpret in its original form. To address this, we expressed the measure as a percentage (e.g. 0.25 shown as 25%) and added a metric explanation feature. This feature presents the definition, formula, and limitations in plain language through an info icon placed next to the legend, allowing students to understand what the map shows without requiring technical background (Appendix Figure B.2). This figure shows the migration module where an info icon placed beside the legend title, describes the metric.

In the early-stage prototype, the population module primarily supported viewing a single topic (see Figure 2). We expanded the population module by integrating additional demographic layers (e.g. racial composition) using a toggle functionality (Figures 4, B.1). Figure 4 illustrates the population module that allows students explore population density over time. Appendix Figure B.1 shows the same population module with the overlay toggle used to switch from population density to racial composition (percent by race) overlay (e.g. White, Black, Mexican, and Native populations).

As shown in Figure 4, the population module helps students connect historical events to population density through place-based inquiry. When a student selects "California Gold Rush (1848)" on the timeline, the map advances to 1850; the year California officially becomes a state. The student reads county-level population density in California and can observe that El Dorado County stands out as highly populated, consistent with the California gold rush. The student can then use the county search to verify additional places and respond to the story panel's AP-style questions by citing the observed density pattern and county values as evidence.

We implemented new modules beyond the initial three (history, population, and migration), including a compare module to address the need for side-by-side (juxtaposed) map comparison (Figure 5) and an immigration module to support immigration related curriculum contents (Appendix Figure B.3). Figure 5 illustrates how the compare tool can reveal uneven coverage of Native Americans that a 1790 census map obscures. For example, a student compares the 1790 county population density with Native lands, sync the views, and zooms to Florida. The census maps shows no counties because Florida was outside U.S. enumeration in 1790,

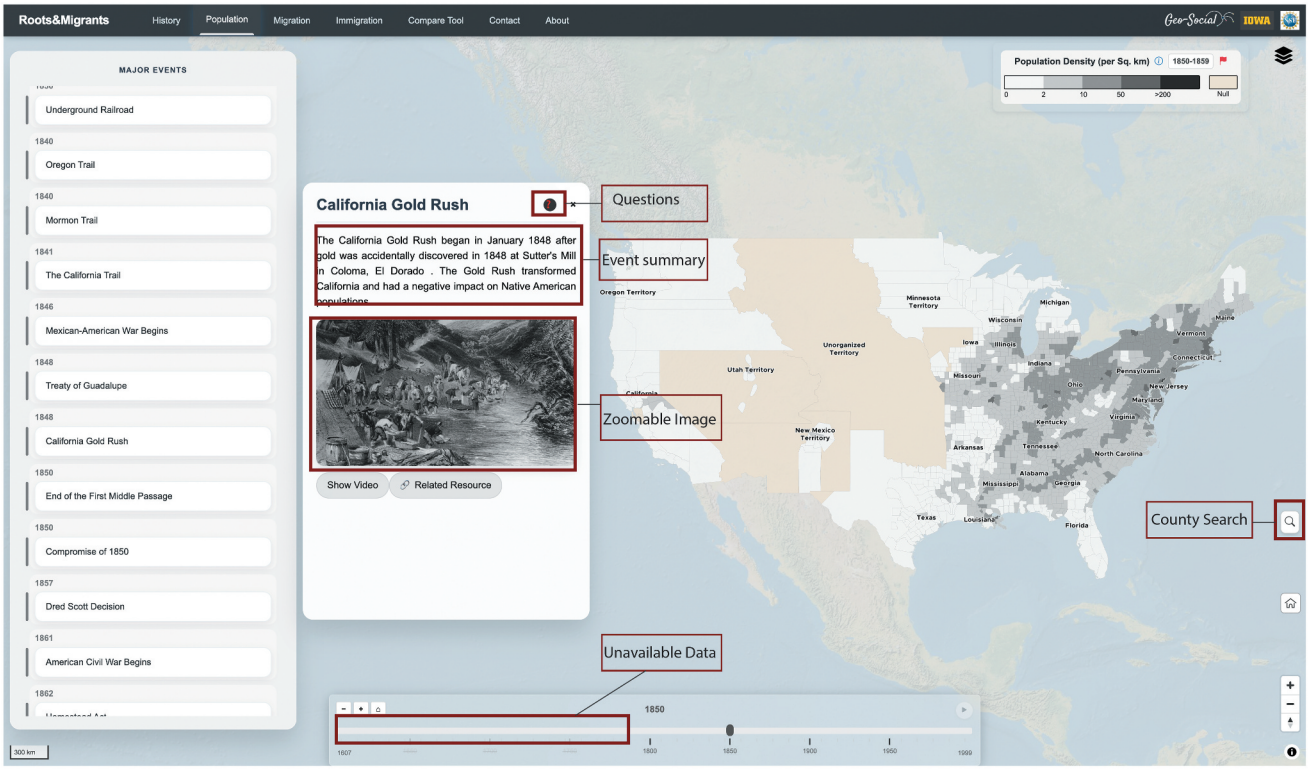


Figure 4. Population module showing interactive features: county search function, embedded questions, and zoomable historical images.

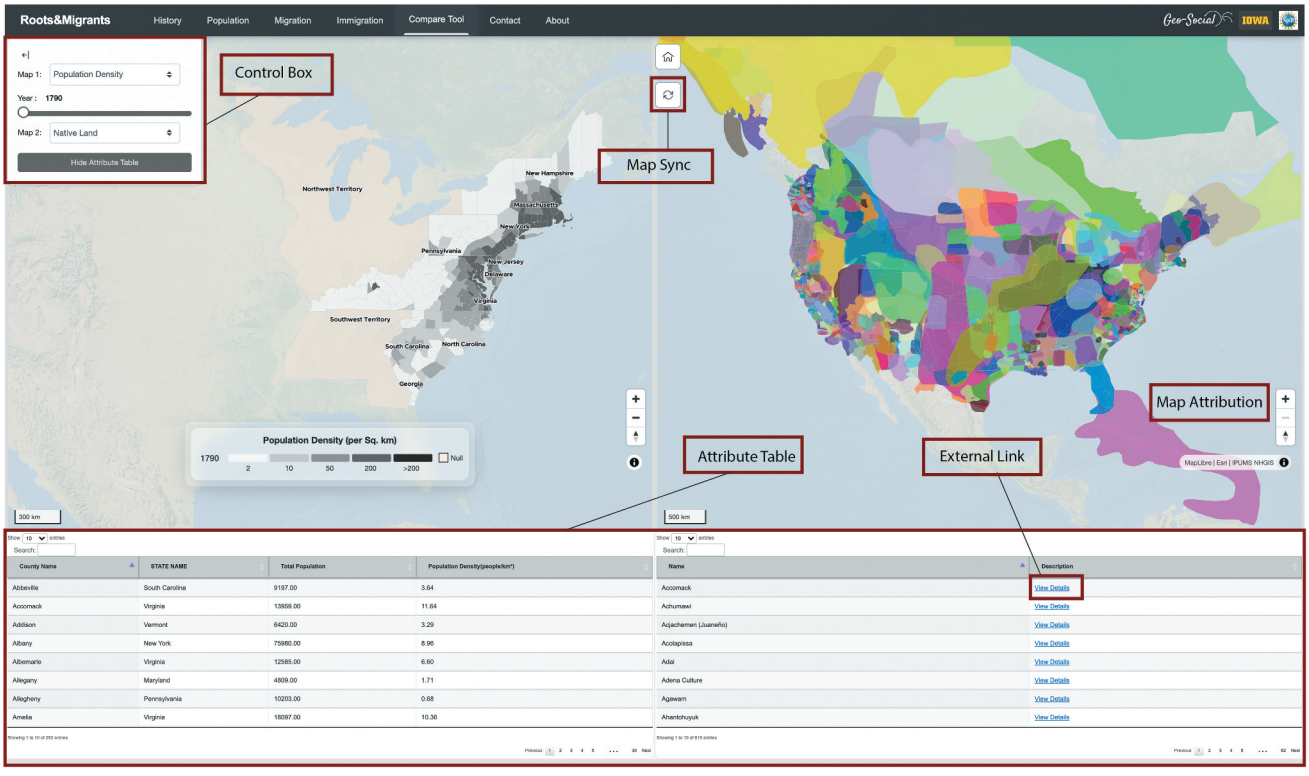


Figure 5. Compare tool interface enabling side-by-side map comparison, map synchronization, data tables, and external resource links.

while the Native lands layer shows Seminole, Miccosukee, and Mayaimi tribes in the same area. Using hover over and the external links within the attribute table, the student can access historical context and draw a conclusion: the absence of Florida from the census map reflects U.S. jurisdictional boundaries, not an uninhabited or unorganized region.

Extended requirements

Based on the focus group discussions and lesson plans, teachers and students developed extended requirements covering multiple areas for improvement. Extended requirements address five key themes: content, visual design, map interactivity, functionality and questions. For content, teachers suggested aggregating data to build personal historical narratives and including specific ethnic subgroups (e.g. Irish populations) in the race composition layer. Visual design suggestions included adding interactive pop-up graphs showing demographic trends on hover. For map interactivity, participants requested improved data filtering, alignment between historical events and their corresponding map displays, and the ability to explore data at multiple geographic scales. Feedback on functionality included reducing the number of modules from five to four, integrating AI support to help students navigate the application, and optimizing performance to reduce lag times. Finally, participants noted that the existing question prompts should be revised to better align with Advanced Placement (AP) assessment formats.

Discussions

Findings from the workshops and formative evaluation show that adoption of educational interactive maps depends less on "what the map can show" and more on whether the system fits instructional practice under classroom constraints such as limited time, curriculum alignment, and student map literacy (Hong, 2016; National Research Council, 2006). These constraints reinforce that educational mapping tools must be designed as instructional systems, where usability, interpretability, and alignment with classroom activities are prerequisites for inquiry-based learning. Also, because students often treat maps as authoritative and objective, their design carries ethical responsibility.

Historical quantitative sources vary in who they capture and how consistently they do so across time and space, which can disproportionately affect underrepresented groups (Koylu & Kasakoff, 2025). For example, Native American populations were often documented through separate administrative record systems such as annuity, allotment, and Indian census rolls, maintained by the Bureau of Indian Affairs (BIA) from 1885 to 1940, rather than through a single standardized enumeration process (National Archives and Records Administration, 2014). Treating maps as objective and complete creates an interpretive risk: students may read missing or unavailable values as historical absence rather than gaps in historical records.

When quantitative coverage is uneven, design choices either reinforce erasure or draw attention to what is missing. We paired quantitative views with qualitative sources and narrative storytelling to avoid implying absence, especially for underrepresented groups whose histories are not well represented in the census or other historical data sources. This design choice reflects a larger concern in critical cartography. As Crampton and Krygier (2005) argue, cartographic conventions are not neutral but shape whose geographies are represented and how they are interpreted. Native Land Digital's layer, for example, was not designed to be overlaid with colonial boundaries or structured through fixed temporal frames (Temprano, 2017), but rather to acknowledge Indigenous presence outside dominant political geographies. Adapting such representations for classroom use therefore introduces important design considerations. In our case, overlaying U.S. territorial boundaries may support teaching territorial dispossession, but also risks reframing the original intent of the data. This points to a broader issue in critical and educational cartography: how critical representations can be adapted for classroom use without being reshaped by the same cartographic conventions they were intended to challenge. This remains a design compromise and highlights the trade-offs that show up when critical maps are repurposed for educational use, requiring more explicit attention in both research and design.

A consistent theme across feedback is that interactivity is most valuable when it is tied to explicit inquiry tasks. Teachers requested prompts that require map-based evidence and, in AP context, guidance that mirrors assessment practices such as structured questions and scoring expectations. This suggests that open exploration alone is rarely sufficient in classrooms; instead, interactive capability is effective when it supports a visible workflow of describing patterns, comparing conditions, and justifying explanations with evidence. These findings are particularly significant in the context of Advanced Placement Human Geography (APHG), which often serves as an important entry point for geographic and spatial thinking in U.S. high schools (Hong et al., 2022; Serrano, 2025). As an introductory AP course,

APHG typically enrolls a broad range of students with varying levels of academic preparation and map literacy. In many schools, it may be the only dedicated geography course offered, making it an important site for developing spatial reasoning skills. This helps explain teachers' emphasis on clarity, usability, and structured inquiry tasks, as instructional tools must support diverse learners while aligning with rigorous AP expectations within limited class time. This reinforces cartographic research that defines interaction in relation to user goals, skills, and tasks rather than as a generic feature set (Andrienko et al., 2003; Roth, 2013).

Workshop feedback also highlights the role of representation in supporting spatiotemporal reasoning for novice users. Teachers noted that some symbology choices and map types, such as proportional symbol maps that encode values only by size, can be difficult to interpret quickly, especially in a classroom setting with limited time. Their preference for clearer symbolization and redundant visual variables reinforces a long-standing cartographic principle: representations should reduce decoding effort so learners can focus on reasoning rather than interpretation (MacEachren, 1995). This point is especially important for spatiotemporal representations, where learners face high cognitive demands in integrating space, time and explanatory variables (Mayer et al., 2023; Mayr & Windhager, 2018).

Teachers strongly preferred comparison tools, noting that juxtaposition reduces memory demands because students do not need to retain prior map states while comparing views. However, their comments also clarify that comparison tools are only effective when paired with consistent legends, comparable classification, minimal data classes, clear labels and metadata. This extends prior work on comparative visualization by emphasizing that comparative interaction is not only an interface feature. Effective comparison also depends on the task, representation and documentation so maps are standardized and interpretable to avoid misleading contrasts or unnecessary cognitive load (Munzner, 2014).

Usability issues raised by students, such as difficulty selecting overlapping polygons and unclickable hyperlinks, emphasize a broader implication: in classroom contexts small interaction failures can negatively impact inquiry because they consume limited instructional time and discourage exploration. For novice users, core interaction operators such as feature identification, selection, filtering, linking, and navigation, are not secondary refinements; they are functional requirements for adoption and learning. These findings highlight that core interaction operations such as selection, filtering, and linking are essential for supporting interpretation in classroom contexts.

Finally, the findings support a shift away from strictly linear story-map interaction as the default model for educational mapping. Teachers valued narrative context, but they emphasized that classroom learning often requires non-linear movement between views, comparison across time periods, and discussion-oriented synthesis guided by lesson structure. This is consistent with recent work on interactive atlases showing that effective designs combine linear and non-linear narrative structures rather than relying on a single approach (Baldrica-Franklin et al., 2025). As a result, classroom instruction should be guided without forcing students through one linear scroll sequence. Instead, instructional structure should be distributed between interface design and co-designed lesson activities, allowing exploratory interaction while still supporting evidence-based reasoning. An important research agenda for cartography and geovisualization is therefore to evaluate educational maps as classroom workflows, where narrative, interaction, representation consistency, and lesson design jointly determine whether students can produce and communicate map-based explanations under real instructional constraints.

These conclusions should be interpreted in light of the study's scope. Student feedback came from a small group in an early-stage design setting, and the participants may not represent the full range of map literacy, classroom routines, or technology conditions. For this reason, our results should be read as formative evidence that clarifies requirements and design directions, and they motivate the next step: larger, teacher-led classroom implementations with more systematic evaluation of usability and learning.

Conclusion

This paper presents a user-centered design study of Roots & Migrants, an interactive mapping platform developed as a case study in U.S. high school history education. The platform combines spatiotemporal maps with narrative context to support inquiry into historical population dynamics while making visible the limits and uneven coverage of historical records. Through two participatory workshops and formative evaluation, we identified recurring classroom constraints, such as limited instructional time, variable map literacy, curriculum alignment, tool complexity, and device compatibility. These constraints were translated into requirements for spatiotemporal inquiry in classroom settings and guided the development of an alpha system designed around by interdependent teacher–student workflows.

The study contributes to cartography and geovisualization by identifying representation and interaction

strategies that support core classroom tasks, particularly temporal comparison, coordinated exploration across views, and interpretability under time constraints. The study also contributes to user-centered design research by demonstrating how engaging teachers and students as interdependent co-designers enables classroom workflows, instructional constraints, and learning goals to be translated into actionable interface and interaction requirements. In addition, the work contributes to ethical cartography and education by showing how design choices can help students recognize population maps as partial historical records shaped by uneven data coverage, rather than neutral or complete representations.

Future work will extend classroom implementation of Roots &Migrants with more systematic evaluation, including classroom observation and task-based assessment. We will also broaden historical coverage by incorporating additional narratives and data sources to better represent migration and population patterns of groups underrepresented in authoritative records including Native American, Black, Mexican, Eastern and Southern European populations. Planned extensions include flow mapping (Koylu et al., 2023) to support origin-destination inquiry and the spatial representation of major migration events such as the Exodusters movement (1870s) and Dust Bowl migration (1930s), alongside multi-scale views that allow key variables to be explored at both state and county levels.

The central takeaway of this work is that educational interactive maps should be designed as instructional systems grounded in user-centered design and cartographic principles. Successful design aligns curriculum goals, representation, and task-based interaction with the needs of teachers and students, while supporting inquiry-based learning and clearly communicating data limitations. Integrating UCD with cartographic design enables interactive maps to support spatiotemporal reasoning under real classroom constraints.

Data and codes availability statement

All data used in the development of Roots & Migrants are openly available from public sources. These datasets are cited and accessible through the Roots & Migrants website at https://rootsandmigrants.com/.

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