RESEARCH ARTICLE SUMMARY

INDIGENOUS PEOPLES

Effects of land dispossession and forced migration on Indigenous peoples in North America

Justin Farrell*, Paul Berne Burow†, Kathryn McConnell†, Jude Bayham, Kyle Whyte, Gal Koss

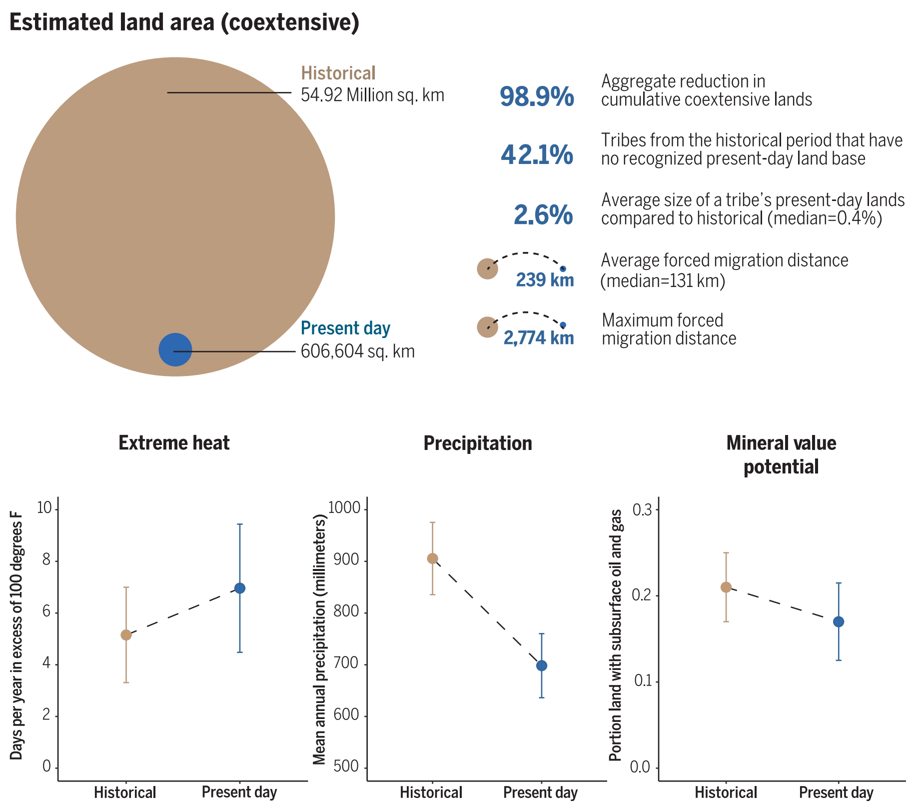
INTRODUCTION: Centuries of land dispossession and forced migration of Indigenous peoples by European and American settlers reshaped the entire North American continent. Yet the full scope of change is not quantified or systematically georeferenced at scale because of severe data constraints. Thus, fundamental questions and hypotheses still remain untested, especially concerning estimated total land loss, land value potential, and current and future climate risks. Building on historical research and Indigenous Studies scholarship, we developed a new dataset to catalog and examine the totality of land dispossession and forced migration in what is currently called the United States and tested hypotheses related to the environmental and economic impacts of these processes over time.

RATIONALE: We constructed a new comprehensive dataset compiled from a broad suite of historical sources for the vast majority of Indigenous peoples, by nation, within the boundaries of the contiguous United States. We classified the land base data for each tribe within two time periods: historical and present day. We then applied statistical models to assess two research questions at scale. First, what was the full extent of land dispossession and forced migration for each tribe and for all tribes combined? Second, did tribes' new lands, being severely reduced in size and potentially far from their ancestral lands, offer improved or reduced environmental conditions and economic opportunities over time? We tested the latter along four hypothesized dimensions that include exposure to climate change risks and hazards; mineral value potential; suitability for agriculture; and proximity to US federally managed lands that limit Indigenous movements, management, and traditional uses.

RESULTS: Statistical analysis shows that aggregate land reduction was near total, with a 98.9% reduction in cumulative coextensive lands and a 93.9% reduction in noncoextensive lands. Further, 42.1% of tribes from the historical period have no federally- or state-recognized present-day tribal land base. Of the tribes that still have a land base, their present-day lands are an average of 2.6% the size of their estimated historical area. Additionally, many tribes were forced onto new lands shared by multiple Indigenous peoples, even in cases in which nations are culturally dissimilar and have separate ancestral areas. Many present-day lands are far from historical lands. Migration dyad analysis shows that forced migration distances averaged 239 km, with a median of 131 km and a maximum of 2774 km.

Tests related to climate change risk exposure, land conditions, and potential economic value reveal substantial differences between tribes' historical and present-day areas. First, tribes' present-day lands are on average more exposed to climate change risks and hazards, including more extreme heat and less precipitation. Nearly half of tribes experienced heightened wildfire hazard exposure. Second, tribes' present-day lands have less positive economic mineral value, being less likely to lie over valuable subsurface oil and gas resources. Agricultural suitability results were mixed. Last, about half of tribes saw an increase in their proximity to federal lands in the present day.

CONCLUSION: This research suggests that near-total land reduction and forced migration lead to contemporary conditions in which tribal lands experience increased exposure to climate change risks and hazards and diminished economic value. The significance of these climate and economic effects reflect aggregate changes across the continent, but there is an urgent need to understand the magnitude of place-specific impacts for particular Native nations resulting from settler colonialism in future research. This study and dataset initiate a new macroscopic research agenda that prioritizes ongoing data collection, Tribal input, historical validation, public data dashboards, and computational analysis to better understand the long-term dynamics of land dispossession and forced migration across scales. ■



Land dispossession and forced migration impacts between historical and present-day periods. (Top left) Proportion reduction for coextensive land area estimation (accounting for multiple tribes in a single area). Areas of circles correspond to estimated land areas. Limitations in the historical record likely result in an underestimation of total historical land area. (Bottom) Plots show changes in tribal land conditions (mean and 95% confidence interval) for selected variables.

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RESEARCH ARTICLE

INDIGENOUS PEOPLES

Effects of land dispossession and forced migration on Indigenous peoples in North America

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What are the full extent and long-term effects of land dispossession and forced migration for Indigenous peoples in North America? We leveraged a new dataset of Indigenous land dispossession and forced migration to statistically compare features of historical tribal lands to present-day tribal lands at the aggregate and individual tribe level. Results show a near-total aggregate reduction of Indigenous land density and spread. Indigenous peoples were forced to lands that are more exposed to climate change risks and hazards and are less likely to lie over valuable subsurface oil and gas resources. Agricultural suitability and federal land proximity results—which affect Indigenous movements, management, and traditional uses—are mixed. These findings have substantial policy implications related to heightened climate vulnerability, extensive land reduction, and diminished land value.

Historical research shows that land dispossession and forced migration are the primary means by which settler populations achieve large-scale political and economic control over Indigenous populations. Early records provide evidence of these practices as early as the 12th century BCE; followed by the Greek, Persian, and Roman empires; and more recently by European colonial expansion across the globe throughout the middle and latter period of the 2nd millennium CE. Native peoples living in what is today North America experienced large-scale forced migration and ancestral land dispossession, beginning with the arrival of European settlers and culminating in 19th- and 20th-century continental expansion by the United States.

Prior research has argued that historical land dispossession and forced migration are part of the broader sociopolitical formation of settler colonialism, which references the process through which Indigenous polities are replaced by a society of settlers whose claims to territory and governance are enabled by the extirpation of Indigenous peoples even as these communities and nations endure in the present (*1*). The primary terms we use to describe First Peoples of the continent are "Indigenous" or "Native" peoples, but we also use "tribe" or "tribal nation" throughout the text to reference both Native peoples and their polities now and in the past in the area that is currently called the United States. At times, including in our title, we reference "North America" rather than the "United States" because our data focus on sovereign tribal nations whose existence precedes the creation of the United States and its borders and still today maintains a government-to-government relationship with the US federal government. The term "North America" recognizes these nations' distinct sovereign political status even as we bound the area of study to the exterior borders of the contiguous United States. Further, many tribal nations maintain land claims that exceed the boundaries of the contemporary United States on the basis of ancestral occupancy, but we do not include those areas in order to control for the varied political-historical contexts of land dispossession in neighboring settler nation-states such as Canada and Mexico and instead focus on US policies toward Indigenous peoples within its nation-state boundaries.

Research shows that land dispossession and forced migration created the groundwork for contemporary conditions in which Indigenous peoples in the United States today face greater vulnerabilities to their health and food security, lack access to culturally appropriate education, and have heightened exposures to contaminants (*2*–*8*). Despite substantial scholarly attention to these issues, research has been primarily qualitative and based on case studies, circumscribed to detailed historical and anthropological accounts, often of an individual tribe or region (*9*–*13*). Or studies have primarily focused on rough estimates of the loss of property as measured in acres, such as the oft-cited figure that 90 million acres of land were lost through allotment of Indigenous lands under the Dawes Severalty Act of 1887 (*14*). Researchers have been unable to quantify these wide-ranging historical developments at large scales because of severe and ongoing data constraints, in which reliable information—which itself was at times suppressed during and after treaty negotiations, land ceding, and dispossession processes (*15*)—is scattered across bureaucratic agencies or buried in state, federal, and Indigenous government archives.

This lack of information creates substantial challenges when seeking to understand the collective impacts of US policies of land dispossession and forced migration on Indigenous peoples today. For without clarity and valid information on migration and dispossession, precise correlative or causal connections are challenging to justify at reliable degrees of precision.

Although prevailing qualitative approaches are indispensable and lay the groundwork for this study, their restricted scope leaves crucial questions unanswered about the totality of land dispossession and forced migration in US history and the aggregate consequences of these outcomes on Native peoples over time and leading up to the present. What was the full extent of forced migration for each tribe and for all tribes combined? What proportion of tribes no longer have any federally and state-recognized land base? We do not know the distribution of relocation distances or aggregate estimates of land area reduction, although analyses of land allotment and economic development show the substantial long-term impacts on wealth for Indigenous nations (*16*). Most critically, we only have limited systematic knowledge about the implications of the environmentally different lands that Indigenous peoples were forced to migrate to. Historical accounts show that settler governments tended to intentionally relocate tribes to what, at the time, were considered less economically desirable lands (*17*). But we do not know, for example, whether Native peoples were systematically forced to lands that are, currently, more or less vulnerable to the effects of climate change. Additionally, did these new lands come to offer Indigenous peoples improved or reduced natural resource–based economic opportunities (such as oil and gas minerals and agriculture), both at the time of relocation and into the 20th and 21st centuries as a multitrillion-dollar land-based settler economy was being built?

Regarding subsurface oil and gas resources, there is a compound issue here of US settlers creating barriers to Indigenous cultural, political, and economic self-determination and then preventing Indigenous peoples from enjoying equal benefits and safety from the emerging resource-based settler economy. But certainly, many Indigenous persons have criticized the terminology of "natural resources" as trivializing their kinship and spiritual connections to place and resist oil and gas industries on their lands. The questions here seek to examine the actions of certain US settlers who did interpret

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lands according to certain perceived quantities and values of natural resources.

Centuries of land dispossession have reshaped an entire continent, and its effects continue to endure. Estimating these developments for the first time with a quantitative macroscopic approach will substantially broaden and deepen scientific understanding; provide a comprehensive public dataset to initiate a long-term computational research program on these increasingly important issues; complement the growing, primarily Indigenous-led efforts to map Native lands across North America and beyond (18–20); and improve future policy-making by uncovering fundamental patterns heretofore unexamined at their full geographic and temporal scope.

New dataset on Indigenous land loss and forced migration

To test these questions, we constructed a new comprehensive dataset of land dispossession and forced migration for the vast majority of Indigenous peoples in the area currently called the contiguous United States. We compiled data from many sources (table S18), including Indigenous nations' own publications and public archives, digitized administrative records of land cession treaties made between Native nations and the US government between 1722 and 1883 (21), judicial records from land disputes filed before the Indian Claims Commission between 1946 and 1978 (22), the Library of Congress and Department of Interior's schedule of Indian Land Cessions in the United States, 1784–1894 (digital scans of Congressional "Schedule of Indian Land Cessions" and "Schedule of Treaties and Acts of Congress Authorizing Allotments of Lands in Severalty") (23), Oklahoma State University Library's digitized "Indian Affairs: Laws and Treaties" seven-volume report from Charles J. Kappler in 1904 to the Senate Committee on Indian Affairs (24), the University of Nebraska Library's American Indian Treaties Portal (25), US Forest Service "Tribal Connections" geospatial data (26), the Bureau of Indian Affairs' data and reports "Indian Lands in the United States" and "Indian Entities Recognized and Eligible to Receive Services from the United States Bureau of Indian Affairs" (27), the Smithsonian Institution's series of reference volumes on Native American studies (28), and a dataset of digitized treaties from prior research (29). We also validated and cross-checked with crowdsourced data from the Indigenous-led organization Native Land Digital that collects, organizes, estimates, and publishes self-reported and secondary evidence of Native peoples' historical locations, including territory maps from Indigenous nations themselves (30). None of these sources are entirely comprehensive, but when aggregated and rigorously cross-checked, they together form a reliable state-of-the-art dataset.

We used a comparative-historical research design with two time periods: historical lands and present-day lands. We define historical lands as the earliest documented locations of Indigenous peoples in the historical data sources (table S18), often as lands held before the last 19th-century forced migration. Constructing the historical data involved difficult decisions concerning scale and historical lineage because contemporary tribes may be groups that identified as varied types of tribal formations during colonial periods even though historically their members may have associated to differing degrees with larger or more fluid social groups that were not themselves organized as "tribes." Indigenous peoples can constitute themselves by clans, kinship networks, or bands, in addition to more variable instances in which multiple tribes form a larger confederation or nation of associated tribes. For example, according to their own historical records (31, 32)—and confirmed in the federal administrative records above—one-third of the Cayuga people were forced from New York to Kansas in 1846. Before European contact in 1450, the Cayuga people had become part of the Haudenosaunee confederation that included Cayuga, Seneca, Onondaga, Oneida, and Mohawk peoples and then later the Tuscarora people in 1722. Although the Haudenosaunee became one of the most important confederacies on the continent, each of these six tribes that make up this confederation are distinct peoples and are treated as such in our data. More examples and detail about the analytical, ethical, and historical difficulty of distinguishing tribes and confederacies are provided in the supplementary materials (materials and methods S7), which detail our conservative aggregate approach and future opportunities for improvement.

Any analysis of Indigenous territories must also account for the constancy of annual and interannual movements locally and regionally, diverse land tenure practices, and fluid geographic boundaries. These were widespread before and during our historical period of measurement, preceding the enforcement of predominantly fixed settler-colonial administrative boundaries in the present day. To account for these fundamental differences across time points, we tailored two different units of analysis: one for historical lands and one for present-day lands.

To measure historical lands, we used a larger unit of analysis that accounts for diverse land tenure practices; accommodates systematic tribal movements, coextensive land areas, and shifting boundaries; and avoids the problematic enforcement of overly rigid perimeters prone to measurement error through underestimation. Because of the historical predominance of settler-colonial administrative boundaries, most national-level administrative data have been continually collected at the US county and county-equivalent (CCE) level rather than the Indigenous governmental level. For the purposes of quantitative analysis, CCEs are especially useful and necessary to examine historical Indigenous territories because these administrative boundaries are often large enough to avoid such measurement error (spatial underestimation) but still defined enough to allow for spatial variation to make large-scale comparisons by using a host of reliable administrative and environmental data.

We paired the Indigenous and other historical sources above with data from the US Department of Interior and US Department of Agriculture (USDA) Forest Service—produced under the Native American Graves Protection and Repatriation Act (33, 34)—that identified the present-day states and counties included wholly or partially within a map cession boundary (35). Using this multisourced process, we geocoded and plotted all historical Indigenous lands within CCEs, creating a binary indicator of whether or not a tribe had territory in a CCE.

Indigenous land tenure systems were varied, so these boundaries create room for multiple modes of occupancy and territorial claiming necessary to construct this dataset and to conservatively—and most reliably—make temporal comparisons about land qualities and climate. And although CCEs proved to be the most methodologically reliable option for large-scale historical study, it is essential to recognize that the restriction of Indigenous peoples to a bounded area is itself a practice and outcome of colonial forced migration (36, 37). Further, because some tribes have systematic migratory land tenure practices, it is impossible and analytically unsound to impose overdetermined historical boundaries. Moreover, even attempts to identify exact historical borderlines again reinforces settler-colonial assumptions about modes of land occupancy, private-property regimes, and permanent geographic limitations not shared by some Indigenous peoples.

Although far-reaching and accurate, continued data collection from oral histories, tribal records, and archaeological records will be needed to elongate and deepen the historical reach of the data, especially for adding smaller unrecognized tribes, communities, and Indigenous homelands. Any missing tribes are a limitation of the historical record and publicly available data and do not constitute definitive evidence relevant to any conflicts or legal claims about the political recognition of particular Indigenous peoples. Only tribes themselves can provide decisive historical boundaries when and where they exist. Further, there are some cases in which the historical data cannot disentangle the forced migration routes of tribes who moved numerous times under such conditions, which can create an incomplete history of when and from where they migrated.

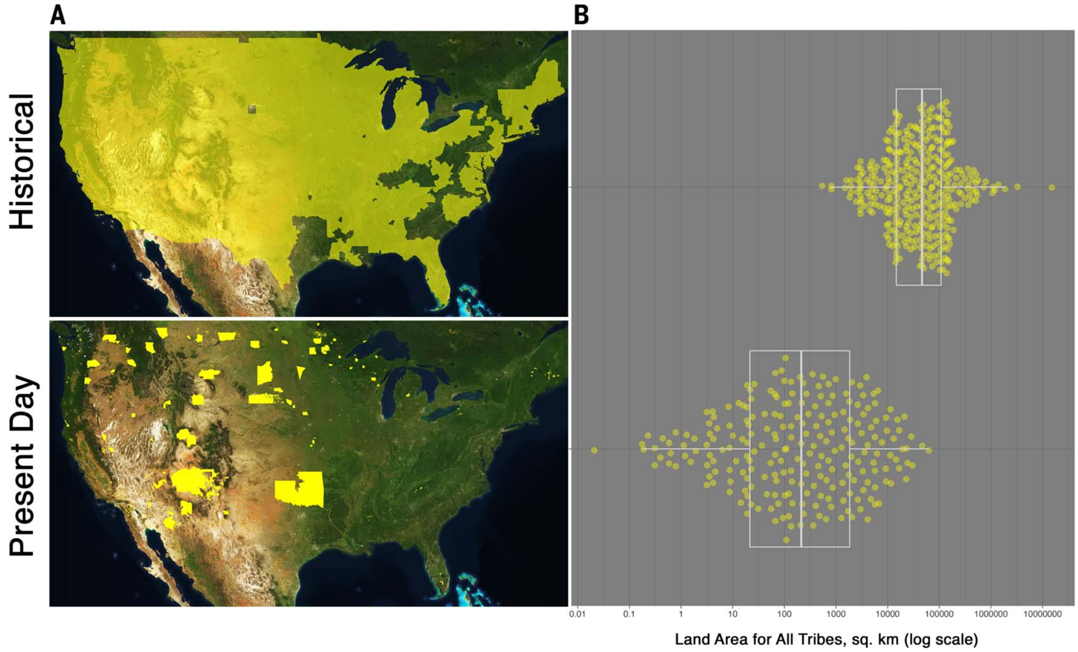

Fig. 1. Historical and present-day locations for all tribes in the data, revealing a sharp decline in land coverage. (Top) Historical. (Bottom) Present day. (**A**) Map showing the aggregate land base for all tribes. (**B**) Plot comparing the total land area of each tribe, revealing a sharp decline from historical territories to present-day lands. Land area values for tribes that drop out between the historical and present-day periods are coded as zero to capture cases of total land base loss. Unshaded areas in both images still have Indigenous historical or present-day land tenure relevance, including for future Indigenous cultural and political self-determination. And limitations in the historical record likely underestimate Indigenous presence in the historical map and can exclude identifiable references to landless or unrecognized tribes. More on this point and the expanded statistical results are provided in table S4 and materials and methods S7.

Although our current analysis is based on data compiled with these historical limitations, the data still capture a preponderance of known cases of Indigenous land dispossession.

For the present day, we measured lands using the finest-grained distinct geographic unit of analysis made available by the US Census Bureau, which is composed of tribal census blocks and block groups that can be aggregated to the tribe level. We used the well-established "American Indian/Alaska Native/Native Hawaiian (AIANNH) Area National Shapefile," which contains precise polygon records for legal and statistical entities, including all federally recognized American Indian reservations and off-reservation trust land areas as well as state-recognized American Indian reservations (*38*). These data include Oklahoma Tribal Statistical Areas (OTSAs), Tribal Designated Statistical Areas (TDSAs), and State-Designated Tribal Statistical Areas (SDTSAs). The relevance of these different land categories is discussed further in the supplementary materials, materials and methods S7.1. These census data allow us to measure present-day tribal lands with precision and reliability.

We then manually paired every tribe's historical land location with its present-day census block group data, a research-intensive process that included matching many tribal and subtribal name variations and locations across historical and present-day time periods to create a total of 616,157 records (full descriptive statistics are provided in tables S1 to S4, and more detailed data collection methods and validation processes are provided in materials and methods S7). In developing and combining these data, we have constructed the most comprehensive paired collection to date, with two tailored units of analysis that ethically and accurately allow for statistical modeling to assess forced migration at a large scale and to compare features of historical lands to present-day lands.

Quantifying land reduction and forced migration

The geographical and temporal distributions of land coverage for all tribes in the data are shown in Fig. 1 and table S4, revealing highly significant differences between historical and present-day lands. We represent aggregate historical land coverage in two different ways to account for the fact that multiple tribes can occupy one territory either at the same point in time or during different historical periods. First and most basically, we computed the total spatial land coverage (Fig. 1A) by summing the area of all polygons with at least one tribe known to be present. This does not consider multiple tribes in a single area but is a more precise estimation of geographical spread across the entire continent. In the historical period, tribes had a documented presence in 7,011,450 km^2 of the area of what is currently called the contiguous United States (Fig. 1A, top). In the present day, tribes had a formally recognized presence in 426,598 km^2 of the area of the contiguous United States—a reduction of 93.9% ($P < 0.001$). Limitations in the historical record likely underestimate Indigenous presence in the historical map (Fig. 1A, top), and unshaded areas in Fig. 1A, top and bottom, still have Indigenous historical or present land tenure and importance, including for future Indigenous cultural and political self-determination.

Second, because some areas were more densely populated with multiple tribes, we computed a cumulative sum of all known historical land areas for all tribes. A single historical location is counted multiple times consistent with the number of tribes with a documented historical presence in it. This measure better accounts for the amount of coextensive shared land across tribes and for the systematic tribal movements and shifting boundaries that characterized the historical period. Across all tribes in the historical period, there was a documented association with 54,919,152 km^2 of land—a figure that was reduced by 98.9% in the present day.

We focused primarily on the differences between known historical and present-day tribal lands, yet notably, 42.1% of all tribes in the dataset with documented historical presence had no federally- or state-recognized land base in the present day. For these tribes, the reduction in their land base was total. Further, in addition to the issue of land area reduction is the issue of the contraction in the number of tribes themselves between the historical period and the present day. Among tribes that still had a land base in the present day (58.2%), their contemporary lands were significantly reduced (Fig. 1B). On average, tribes' present-day lands are 2.6% the size of their estimated historical areas (median = 0.4%). In raw terms, on average these tribes saw a reduction of 215,308 km^2 from

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Fig. 2. Illustration of geographic dispossession and forced migration by using a sample tribe from the data, the Modoc people. These are not step-by-step migration points but are basic dyads comparing in yellow (*1*), lands documented to be held before the last forced migration, with in blue (*2*), current jurisdictional homelands in both Oregon and Oklahoma. Red arcs help to illustrate general land reduction and forced migration patterns.

the documented historical period (median = −67,289 km^2). Without exception, every present-day tribe has a smaller land base than they did in the historical period. Additionally, many tribes were forced onto lands shared by multiple Indigenous peoples, even in cases in which nations were culturally dissimilar and ancestral areas separate.

After demonstrating aggregate levels of land reduction, we next analyzed forced migration and its consequences. To do this, we created a migration dyad for every Indigenous nation, comparing all historical land areas to all present-day land areas. Because some tribes were historically spread across many areas—sometimes involving great distances—we recorded every possible migration dyad (n = 716,856) between every possible historical and present-day location for each tribe. For all possible dyads, the average distance for a tribe between historical and present-day lands was 239 km, with a median of 131 km. The Kickapoo people recorded the furthest total average distance (1366 km), and the Modoc people (Fig. 2) recorded one of the longest single instances from historical lands in the Klamath Basin of what is now California and Oregon to Ottawa, Oklahoma (2565 km). We detailed these migration dyad results with the recognition that not all tribal members of a given Native nation, either now or in the past, live exclusively on tribal lands. But as an approximation of where people of a given tribe live, changes in the location of the tribal land base still accurately demonstrate overall spatial patterns of forced migration.

Long-term impacts: Climate change exposure and natural resource endowments

Did the new lands, despite being severely reduced in geographical density and spatial coverage, offer tribes improved or reduced value and opportunity? We do not ask this question in the spirit of the diverse values that tribal members held at the time regarding their relationships with land. Rather, we ask this question with regard to the values of the territorial economy that US settlers and the federal government forcibly created. We assessed the degree to which tribes were advantaged or disadvantaged in the wake of land dispossession to participate equally in that economy. To investigate this, we compared each tribe's historical lands to their present-day lands across multiple environmental and natural resource dimensions.

We examined four critical dimensions: (i) exposure to climate change risks and impacts, (ii) mineral value potential of lands, (iii) suitability for agriculture, and (iv) proximity to US federally managed lands. The primary difficulty of comparing historical lands to present-day lands is that nearly all land in the United States has been affected by resource development, industrialization, and other US-sanctioned economic development activities during the 19th and 20th centuries and up until the present. We overcame these methodological difficulties by using indicators that are largely durable across time or not heavily affected by the human inhabitants (annual precipitation, oil and gas resources contained within hydrocarbon fields and sedimentary basins below the Earth's surface that formed over hundreds of millions of years, elevation, and terrain ruggedness). However, we purposefully include proximity to US federal lands because that is mutable across time, allowing us to test hypotheses concerning the potential social and political consequences of present-day tribal lands' proximity to these protected lands. Last, we precisely measured these four dimensions using reliable indicators at fine spatial resolution, which we aggregated at the CCE and tribal census block level.

First, we examined climate change risks and impacts using four indicators: extreme heat, long-term drought severity, annual precipitation, and wildfire hazard potential. Our measure for extreme heat is the average of days per year with a maximum temperature over 100°F (~38.8°C)—a threshold that research shows to have especially deleterious health impacts (*39*)—constructed by using data from gridded (4-km resolution) gridMET (*40*, *41*). We measured long-term drought severity using weekly Palmer Drought Severity Index (PDSI) data from *gridMET* (*42*) that includes mean and median weekly drought conditions and "captures the basic effect of global warming on drought through changes in potential evapotranspiration" (*43*). Annual precipitation is also affected by climate change (*43*) and is reliably correlated with agricultural value in nonirrigated arid areas (*44*), and thus we include a standard measurement of annual precipitation based on the standard 30-year normals (1981–2010) developed by the PRISM Climate Group at Oregon State University (*45*). Last, climate change is also linked to increasing wildfires in the United States (*46*), affecting ecosystem services, local economies, air quality, and human health. We constructed a measure of mean and median wildfire hazard potential for all grid cells within a CCE using the gridded (270 m) index from the US Forest Service Wildfire Hazard Potential (WHP) data (*47*).

Noticeable differences between historical and present-day lands are shown in Fig. 3 across several measures of climate risk exposure and mineral potential. The distribution of extreme heat days is shown in Fig. 3A in log scale. Although the mode of the historical and present-day land distributions is similar, tribal lands in the present day experience more extreme heat days. We formally tested whether the distributions are different using a Kolmogorov-Smironov (KS) test. The KS test indicates that the historical and present-day distributions are different with a statistic of 0.14 (P < 0.05). A detailed description of the methods is available in the supplementary materials. We supplemented our analysis with a series of regression models designed to test the difference in mean heat days in the historical and present-day lands (detailed descriptions and robustness checks on every model are provided in tables S5 to S17). All inference is based on robust standard errors. We implemented several alternative specifications and included the Bonferroni adjustment to correct for testing multiple hypotheses. Our results indicate that present-day lands endure nearly two additional extreme heat days per year compared with their historical lands [1.81, 95% confidence interval (CI): 0.49, 3.13].

In addition to extreme heat, we evaluated other measures of climate change risk exposure, including drought, precipitation, and wildfire hazard potential. We found that the present-day distributions are statistically different from the historical distributions for drought (KS statistic 0.55) and precipitation (KS statistic 0.22). Average annual precipitation has declined by nearly 23% in the present-day lands relative to historical lands (−207 mm, 95% CI: −270.00, −144.48) (Fig. 3B); 36.3% of tribes experienced increased drought between the historical and present-day. Aggregate mean drought conditions decreased (0.40 PDSI, 95% CI: 0.26, 0.53). Last, we did not find aggregate mean differences for wildfire hazard potential (0.03, 95% CI: −0.07, 0.14). Although the historical and present-day wildfire hazard potential distributions are not statistically different, the longer right-tail distribution of greater wildfire hazard in the present day demonstrates that many tribes do face significant wildfire risk today. And our data show that

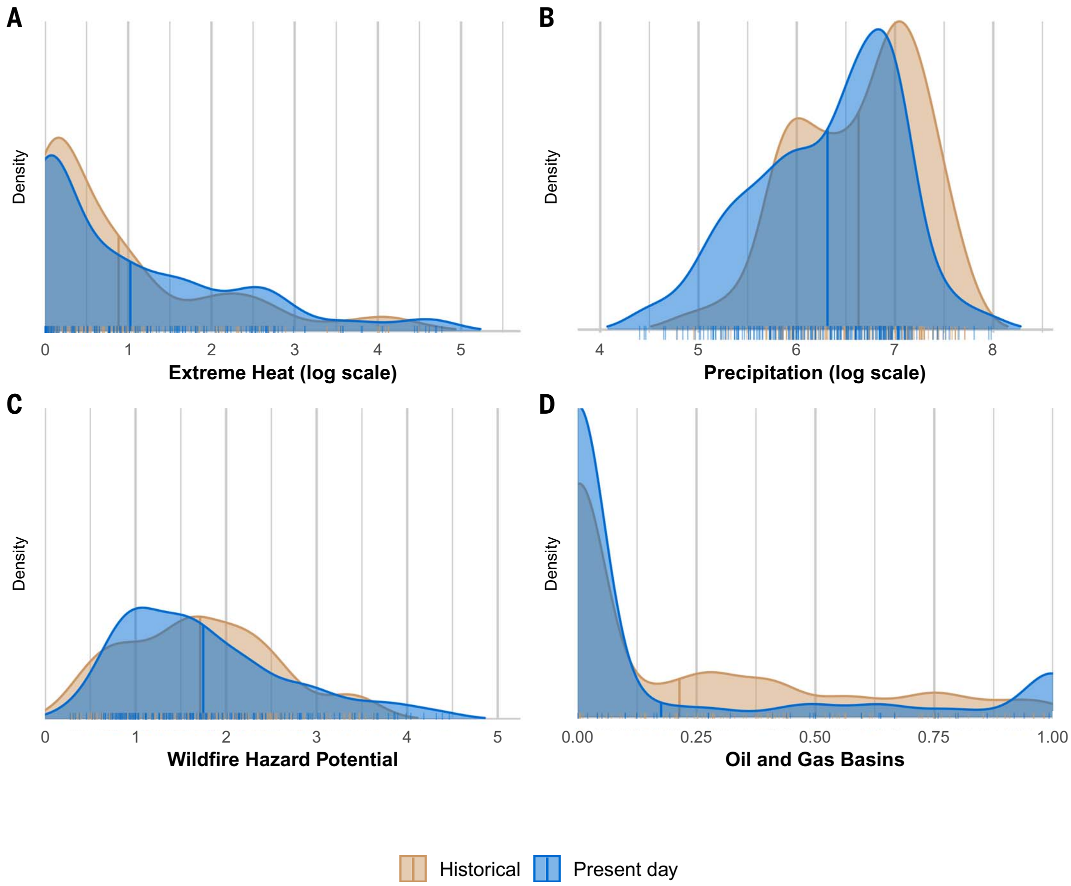

Fig. 3. Plots of differences between tribes' historical and present-day lands. (**A** to **D**) Descriptive increases on present-day lands. (A) Days of extreme heat (temperature above 100°F/~38.8°C), in log scale. (B) Precipitation (millimeters), in log scale. (C) Wildfire hazard potential (scale from very low to very high, with 5 being highest risk). (D) Decreases in oil and gas basins (proportion of tribal land on top of oil and/or gas basin). Means are indicated in all plots with vertical lines. Plots for all variables are available in fig. S1.

47.7% of tribes saw increased wildfire risk on present-day lands relative to their historical lands. Given that wildfire hazard reflects both climatic and anthropogenic factors tied to settler land management regimes, these results offer initial insight into the acute vulnerability that many tribal nations face from the risk of wildfire.

Although present-day lands endure more severe heat and less precipitation, we also sought to assess the positive economic mineral value potential beneath these lands. Again, positive economic mineral value is understood in terms of values tied to the territorial economy it forcibly created. Like our climate change measures, our primary indicator of mineral value is durable across time, recording the fraction of land that sits on top of a subsurface sedimentary basin containing oil and gas minerals. Data for this variable come from the US Energy Information Administration's shapefile of all sedimentary basin boundaries in the continental United States (*48*). The distribution of lands overlying sedimentary basins is lower in present-day lands than historical lands (KS statistic, 0.23) (Fig. 3D). Because of the disproportionate amount of oil and gas beneath Oklahoma Tribal Statistical Areas, we examined statistical differences with and without the OTSAs in the model (table S13, models 1 and 3). In our main model (table S13, model 1), the results indicate that present-day lands are 19% less likely to lie over subsurface oil and gas resources (–0.04, 95% CI: –0.07, –0.005), and when we exclude OTSAs (table S13, model 3), present-day lands are 24% less likely to lie over subsurface oil and gas (–0.04, 95% CI: –0.07, –0.01). These findings provide evidence that tribes were moved to lands with less mineral value potential.

To supplement this finding, we included two auxiliary variables that are highly correlated with the location of oil and gas sedimentary basins but instead are contingent on social and political conditions over time. We included these because they may provide a slightly different means to understand the historical long-term effects of forced migration on the positive mineral value of tribal lands. Although we address the presence of resource endowments, our analysis does not capture the institutional factors that are shown to limit use of resource endowments, such as land ownership, fragmented patterns of land ownership, fractionation, or complex property rights regimes common to many Indigenous nations in the United States (*48*, *49*). Our measures come from US Geological Survey data that record the presence (in cells of one-quarter square miles) and production status of every oil and gas well drilled between 1859 and 2005 (*50*). These data, which include more than 3 million wells, were overlaid on our tribal lands data to create two variables—one for the portion of lands with oil-producing wells and another for the portion of lands with gas-producing wells—which together are a reliable measure of energy development on every individual land area over 146 years.

The results indicate that the majority of present-day tribal lands have a very small proportion of land with oil-producing and gas-producing wells. The KS test suggests that the present-day distributions differ from the historical distribution (oil KS statistic: 0.40; gas KS statistic: 0.54). With the OTSAs included, the difference between the present-day and historical mean proportion of land having actively producing oil or gas wells is not statistically significant. When we excluded OTSAs, we found significant declines for oil production, declining 50% (–0.01, 95% CI: –0.02, –0.002). These supplementary findings suggest that land dispossession limited tribes' capacity to participate in the resource extraction economy to the same degree as that of settlers.

Next, we assessed the suitability of land for agriculture, an essential human activity that sustains societies and produces economic value for communities (*51*). Plant cultivation practices vary across human history, but all require access to land. Although near-total land reduction (Fig. 1 and table S4) affects future agricultural possibilities more than any other factor, examination of such possibilities is still of value, even on severely reduced land areas. Research has shown that land with certain physical characteristics—such as its elevation, terrain ruggedness, and soil properties—plays a critical role in making agriculture possible, productive, and transportable to markets (52, 53). We measured these physical factors in ways that are largely durable across time, enabling us to compare historical lands with present-day lands. We used terrain elevation data from the US Geological Survey (USGS) (54) to estimate changes in elevation and landscape ruggedness. Ruggedness is a common measure that describes the degree of topographic heterogeneity in an area—for example, a steep, mountainous region would be considered highly rugged. Thus, lands characterized by increased terrain ruggedness limit economic activity by inhibiting the mobility of goods and people, just as higher-elevation lands are generally less suitable for agricultural development, depressing its economic potential. The durability of soil organic carbon is questionable given the impact of land-use practices, but we cautiously include it here with that caveat (materials and methods S2.7). We found that present-day lands lie at nearly 21% lower elevation than that of historical lands (–155.65 m, 95% CI: –188.38, –122.93), and present-day lands are concentrated in 29% less rugged terrain (–2.84, 95% CI: –3.70, –1.97]). We found that soil organic carbon is similar in the present-day and historical lands (–0.18, 95% CI: –0.42, 0.07). However, we did find a 28% reduction in soil organic carbon in present-day lands when focusing only on OTSA tribes (–0.61, 95% CI: –0.88, –0.33). These results suggest that present-day lands may be, on average, more suitable for agriculture than were historical lands. However, a major caveat and alternative interpretation of these results is that Indigenous historical land areas were not only much larger but that these declines in ruggedness and elevation suggest that their historical lands spanned areas with more topographical diversity on average, such as high-mountain areas in the western half of the continent, many of which are now publicly owned and predominantly managed by the US Department of Interior and USDA Forest Service. These findings should also be interpreted alongside the findings above that present-day lands receive less precipitation and experience more extreme heat—and more fundamentally, alongside the near-total reduction in land described here, given that access to land at scale is itself necessary for agriculture.

Last, we further examined the effects of forced migration by bringing these data to bear on longstanding questions about the relationship between tribal lands and more than 640 million acres of lands that would come to be claimed and managed by the US federal government. The majority of these lands—which make up nearly 30% of all land in the United States—are handled by four agencies: the Bureau of Land Management, US Forest Service, US Fish and Wildlife Service, and National Park Service (55). Using the USGS Protected Areas Database and shapefile, we constructed a measure that records the total proportion of federally protected land within 160 km (100 miles) for all land areas in the tribal data (56). Historically, these lands that would become US "public lands" were initially viewed by settlers as empty land and of little intrinsic or economic value before the conservation movement in the late 19th century, which ushered in new institutions and legal regimes for their protection and management often predicated on the dispossession of Indigenous lands (57–59).

Building on our findings above about total land reduction (Fig. 1 and table S4), we hypothesized that forced migration patterns may have resulted in tribes being moved to these areas that were geographically rural, "unsettled," and perceived to be of less economic value. Our results suggest that the present-day distribution of lands with federally managed land within 160 km differs from the historical distribution (KS statistic 0.2). A comparison of density plots (fig. S1) reveals that present-day tribal lands are multimodally distributed, suggesting that one group of tribes is proximate to a large portion of federal lands, whereas others are not. Aggregate mean differences are nonsignificant [0.001, 95% CI (–0.01, 0.01)], but we found that 46.2% of tribes saw an increase in their proximity to federal lands in the present day, compared with historical lands.

Further work is needed to elucidate the distribution of change in particular places in the present day. Nevertheless, in line with previous historical research (57–59), it provides initial evidence that some tribes were forcibly moved to historically less desirable and less valuable areas of the continent. It also suggests that by being moved, some tribes were now more proximate to neighboring lands that would come to have rigid bureaucratic boundaries that restrict traditional tribal movements, management, and ecological uses. However, the proximity of Indigenous lands to federal lands, although frequently restricting important cultural uses, may in some cases protect areas from natural resource development depending on its land status and management, allowing for uses that are disrupted by private property ownership. Additionally, federal lands may offer the opportunity for tribal land recovery on a larger scale than the purchase of private lands at fair market value. Nevertheless, dispossession and US settler land management required taking on government structures stemming from the Indian Reorganization Act, the Indian Self-Determination and Education Assistance Act, and other laws and policies (60–64). During the Indian New Deal period (1930s), and later with what is sometimes called the tribal self-determination era (1970s to present), tribes were given incentives and threatened penalties if they did not organize as a formal corporation or as a state-like bureaucratic entity. Tribal governments must operate under strict rules and regulations that some have argued are unfair. The breakup of reservations led to jurisdictional situations of high bureaucratic and managerial complexity for some tribes because their lands involve fragmented trust and fee lands (for example, checkerboarding), as well as the presence of properties with fractionated ownership (for example, multiple owners). The US management of neighboring lands was now controlled by federal "multiple use" policies intended to maximize value for the US territorial economy from which settlers sought to benefit, through timber harvest, recreation, livestock grazing, and oil and gas development (65).

Discussion

This large-scale quantification and georeferencing of land dispossession and forced migration provides macroscopic empirical insight into ongoing efforts across many fields to better understand the path dependencies that have led to unequal distributions of socio-environmental risks and rewards. Our results show that in addition to a significant aggregate reduction in land density and spread, Indigenous peoples were pushed to lands that are now more exposed to climate change hazards; less likely to lie over subsurface oil and gas resources; and many tribes saw an increase in proximity to federally managed lands that may limit traditional tribal movements, management, and uses. Many tribes saw their entire land base dispossessed, resulting in the complete elimination of potential environmental amenities and risk exposure that may have come with a tribal land base, in addition to the fundamental importance of land and political recognition for Indigenous self-governance, cultural practices, and social identities. Although these results are of substantial relevance to many fields across the qualitative and quantitative social sciences, we also present this study as a new methodological paradigm and agenda for continued large-scale empirical investigation into these relationships.

Because of the chronological, qualitative, and ethical difficulties of collecting and validating data at this scale, this study still faces quantitative limitations imposed by the historical record, and thus, research must prioritize ongoing collaboration, collection, and refinement that builds continually from tribal oral histories, reliable crowdsourcing, and Indigenous and settler archival records. Until now, there have been no academic-level repositories to encourage such large-scale aggregation and collection of multiple sources of data. The new dataset is now online and includes a function by which tribal members and others with historical knowledge can submit geographical additions that will be validated, integrated, and openly shared. Reliable data updated in perpetuity from multiple sources will enable future work to improve on this initial attempt and is critical for the continued development of a new macroscopic research agenda. In the future, it will be particularly important to include First Nations and other Indigenous polities in the regions that now include Canada and Mexico because many nations have homelands that transcend contemporary settler nation-state boundaries.

The findings suggest that as society seeks to address its greatest problems—climate change, land degradation, and economic and social inequality—we ought to construct policies with the scientific knowledge that these problems disproportionately affect Indigenous peoples. As a result of land dispossession and forced migration, Indigenous peoples now face increased climate vulnerability, diminished economic value of their lands, and for some tribes, restrictive federal land management regimes, which included strategic exclusion by the United States from equal participation in the emerging energy and industrial sectors that the US federal government valued and became pivotal to its future territorial economy. Science can never quantify the depth of social and cultural trauma, economic deprivation, and political marginalization of losing entire land bases and ecosystems. But the results here contribute fundamental knowledge about the factors that produced current inequities and future risks and should be especially useful for creating policies for restitution. For example, proximity to federal lands may offer an opportunity and institutional pathway for the restoration of erstwhile tribal lands (*66*–*68*).

Our results challenge common approaches to climate change policy-making, revealing the need to better integrate ethics and justice principles by addressing the disproportionate harms that climate destabilization, federal land management, and energy industry operations cause to Indigenous peoples. National-level climate policy often takes an ahistorical approach to mitigation and adaptation activities, emphasizing net reductions in greenhouse gases. Yet, for Indigenous peoples, historical land dispossession and forced migration themselves have created the conditions that intensify climate change vulnerability and risks. These factors include confinement to lands with heightened vulnerability to climate change, restrictions on the mobility of Indigenous peoples to exercise important adaptation options, and degradation of lands because of heightened fossil fuel and other natural resource extraction activities. The immense scale of land dispossession and forced migration provided the settler land base for widespread fossil fuel extraction across North America, which in turn has generated harms and risks to tribal homeland jurisdictions (*69*). Indigenous ancestors did not consent genuinely or at all to land dispossession and forced migration. Their descendants do not consent to the idea that the legacies of historical wrongdoing should today be considered acceptable or beyond redress (*70*–*72*).

There is a remaining climate-related responsibility on the part of nation-states to acknowledge and mediate the most harmful results of dispossession and forced migration. Yet with any policy debate about reparations or restorative justice, one major issue is how to make an accurate assessment of the scope of the historical wrongdoing.

This study shows that the heightened climate vulnerability of Indigenous peoples can be attributed to prior national policies and actions that resulted in massive changes in land tenure and land use. Thus, addressing climate change impacts requires not only attention to the immediate or future impacts of discrete environmental changes but also recompense for past policies and actions that continue to burden particular groups, such as Indigenous peoples. Although decisions to dispossess land from Indigenous peoples were not made with an understanding of future rises in global average temperature, they were nonetheless intended to remove Indigenous peoples as barriers to the interests of settler and migrant populations and foreign investors.

In the most recent US National Climate Assessment (*73*), the "Tribes and Indigenous Peoples" chapter focused on documenting vulnerability to climate change. The cited literature references scientific and tribal perspectives that suggest that land loss or forced migration is at the heart of vulnerability to climate change. An implication is that climate-adaptive responses would involve addressing the particular climate-related issue, such as coastal erosion or extreme heat, but would also address factors affecting landscape resilience that are rooted in historical land dispossession and forced migration. Yet those working at federal, tribal, state, or local government or working for nongovernmental organizations and universities often do not have an accurate grasp of the details, scale, and scope of dispossession and migration. This study represents a new macro-level attempt to provide such information at a large scale and serves as a basis not only for ongoing efforts to mitigate future impacts of climate change but also for new policies to remediate the historical causes responsible for generating vulnerability in the first place.

Materials and methods summary

We constructed the dataset using a wide range of publicly available historical settler and tribal sources, a process involving substantial analytical difficulties and ethical concerns laid out in the main text above and in greater detail in the supplementary materials. Historical estimates for every tribe were linked qualitatively, case by case (616,157 records), with the more spatially resolved present-day tribal census block and block group data. Our land characteristic statistical analysis uses the tribal area and time period as the unit of analysis, but tribe- and reservation-level data are also available in the dataset. Summary statistics for all variables are presented in the supplementary materials, materials and methods S1 and S2. We made historical comparisons using a series of regression models and KS tests. We implemented several alternative specifications, and inference is based on robust standard errors (tables S5 to S17). A detailed account of all data and methods is provided in the supplementary materials.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abe4943
Materials and Methods
Fig. S1
Tables S1 to S19
References (*74*–*82*)

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Science

Effects of land dispossession and forced migration on Indigenous peoples in North America

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Long-term impacts of land dispossession
To date, we lack precise estimates of the extent to which Indigenous peoples in parts of North America were dispossessed of their lands and forced to migrate by colonial settlers, as well as how the lands that they were moved into compare to their original lands. Farrell *et al*. constructed a new dataset within the boundaries of the current-day United States and found that Indigenous land density and spread in has been reduced by nearly 99% (see the Perspective by Fixico). The lands to which they were forcibly migrated are more vulnerable to climate change and contain fewer resources. Research and policy implications of these findings are discussed. —TSR

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