

**Quantifying information content using population genetics concepts and equations to develop new insights into information distribution in human communities**

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**Abstract**

Information evolves within human societies in ways that parallel the evolution of genes in biological populations. Applying classical population genetics equations, we developed a framework in which the rates of learning and forgetting define the net balance of informational change, and directional exchange among groups can be represented as information flow. We apply this framework to a 43-year corpus of policy documents, court decisions, and media

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coverage concerning grizzly bear (*Ursus arctos horribilis*) management. We quantified topic turnover, temporal trends, and pairwise information flow among executive, legislative, journalistic, and Non-governmental Organization actors. Directional flow analyses revealed that journalists and executive actors were key sources of information influencing legislative uptake in conflict and legal discourse. In contrast, governmental actors shaped the communication of Non-governmental Organizations within science themes. These findings provide a foundation for examining how conservation information diffuses through governance systems.

Keywords: conservation policy; grizzly bear management; information diffusion; policy diffusion; population genetics

### **Introduction**

The gradual accumulation of genetic mutations across generations underlies the diversity of life observed today. This incremental process of change also characterizes the evolution of ideas and knowledge within human societies (Caldwell and Millen 2008). Analytical tools from biology, such as phylogenetic analyses that reconstruct historical relationships among species based on shared ancestry (Kaya et al. 2022), can similarly be used to trace the lineage of information, revealing how ideas branch, merge, or disappear over time. For example, researchers have applied phylogenetic techniques to the lineage of Chaucer's manuscripts, uncovering how hand-copied texts changed and diversified with each iteration (Barbrook et al. 1998). Such examples demonstrate that evolutionary frameworks can extend beyond biology to study how information arises, persists, and diverges within human populations, clarifying how information flows through social networks and shapes decision-making in contexts such as conservation and environmental policy (Cash et al. 2003; Rogers 2003).

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Information accumulation and transformation are fundamental to what makes human societies distinct from other species (Whiten et al. 2022; van Leeuwen et al. 2024; Aplin et al. 2025).

These processes, often framed as cultural evolution, have long been modeled using tools adapted from evolutionary biology and quantitative genetics (Fogarty et al. 2024; Kandler and Shennan 2013; Laland et al. 2001). In this view, cultural traits or “bits” of information (Cartuyvels et al. 2021) function as heritable units subject to selection, mutation, and drift, much like alleles in genetic populations. By modeling how innovations emerge, spread, or disappear, researchers have shown that the same mathematical principles describing genetic change can provide insight into the tempo and mode of cultural change (Henrich 2016; Mesoudi et al. 2006). Yet despite these conceptual parallels, translating them into measurable, population-level frameworks remains challenging (Mesoudi 2017; Creanza et al. 2017). Addressing this gap requires tracing how information diffuses, mutates, and stalls within communities, processes that influence trust, uptake, and collective action (Shipan and Volden 2008; Rogers 2003). Classic population genetic models of variant acquisition, retention, and loss can help address this gap by providing a framework for quantifying information acquisition, retention, and loss within human populations (Cavalli-Sforza and Feldman 1981; Henrich 2016).

Population genetics examines how allele frequencies change over time due to mutation, drift, and gene flow (Hohenlohe et al. 2021; Holsinger and Weir 2009; Lenart et al. 2022; Mélachio et al. 2015). These core processes collectively determine how genetic diversity arises, persists, and moves through populations, and can be expressed mathematically as changes in allele frequencies or total variation over time as functions of mutation ( $\mu$ ), loss ( $\delta$ ), and migration ( $m$ ). Such models provide a concise framework to represent population-level evolution as the balance of gain, loss, and exchange.

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If we treat pieces of information as analogues to alleles, then the learning, forgetting, and sharing of knowledge among people or institutions become the social equivalents of mutation, drift, and gene flow. Learning introduces new information into a population's collective knowledge pool, much like mutations introduce new genetic variants into a gene pool (Foster 2006; Lang and Murray 2008). This "mutation" of information arises through education, innovation, and cultural transmission. The expected change in information due to learning can be expressed as

$$\frac{dK_i}{dt} \Big|_{learn} = K_i \mu \quad (1)$$

where the change in  $K_i$  due to the contribution of learning in a population is reflected by the total amount of information in population  $i$  at time  $t$  and the learning rate  $\mu$ , analogous to the genetic mutation rate. This represents the probability of acquiring new information, and  $K_i$  describes the total amount of information present in population  $i$  at a given time. As the information base grows, opportunities for further learning increase, producing exponential information growth when  $\mu > 0$ . Analogous to genetic drift, forgetting or disuse causes information to decay over time:

$$\frac{dK_i}{dt} \Big|_{forget} = K_i \delta \quad (2)$$

where the change in  $K_i$  due to the forgetting of information in a population is reflected by the total amount of information in population  $i$  at time  $t$  and the forgetting rate  $\delta$ , which is a constant rate of information loss indicating the probability that a piece of information is lost per unit time. The rate of loss is proportional to the amount of information present, leading to exponential decay when forgetting dominates learning. Combining equations (1) and (2) gives:

$$\frac{dK_i}{dt} = K_i (\mu - \delta) \quad (3)$$

where the rate of change in total information in population  $i$  over time is influenced by the rate of information gain due to learning and the rate of information loss due to forgetting. This differential equation models the balance between learning (the introduction of new information) and forgetting (the loss of existing information). The solution to this equation describes how the total information in a population evolves over time, depending on the relative magnitudes of  $\mu$  and  $\delta$ . For example, if  $\mu > \delta$ , the term  $(\mu - \delta)$  is positive, indicating that the population's information is increasing over time and if  $\mu < \delta$ , the term  $(\mu - \delta)$  is negative, indicating that the population's information is decreasing over time. When  $\mu = \delta$ , the net effect is zero, meaning the total information remains constant, supporting a globally stable equilibrium value for the total amount of information in the absence of other forces. Although information bits can still change over time, when  $\mu = \delta$  total information will remain constant over that time period.

Beyond learning and forgetting, information transmission describes the movement of ideas between groups such as communities, organizations, or institutions (Ammar et al. 2023; Kashima et al. 2019; Kunst and Mesoudi 2025; Mesoudi 2021). This process enriches the collective information pool by allowing information from one population to enter another. The rate and effectiveness of transmission can substantially influence overall information dynamics and are defined as:

$$\frac{dK_i}{dt} = m(K_j - K_i) \quad (4)$$

where  $K_i$  is the quantity of information in the focal population  $i$ ,  $K_j$  is the amount of information in another population  $j$ , and  $m$  is the rate of information transmission between  $i$  and  $j$ , analogous to the migration rate in population genetics. This equation shows that if  $K_j > K_i$ , information flows from  $j$  to  $i$ , increasing  $K_i$ . Incorporating learning, forgetting, and transmission gives:

$$\frac{dK_i}{dt} = K_i(\mu_i - \delta_i) + m(K_j - K_i) \quad (5)$$

where the learning rate in population  $i$  is defined by  $\mu_i$ , the forgetting rate in population  $i$  is defined by  $\delta_i$ , and the net information flow due to transmission from population  $j$  to  $i$  is defined by the product of  $m$  and  $(K_j - K_i)$ . For multiple interacting populations, this can be generalized as:

$$\frac{dK_i}{dt} = K_i(\mu_i - \delta_i) + \sum_{j \neq i} m_{ij}(K_j - K_i) \quad (6)$$

where  $m_{ij}$  represents the transmission rate specifically between populations  $i$  and  $j$ . This generalization captures complex networks of information flow.

Together, these processes describe a dynamic system where innovation and learning add new information (mutation), forgetting removes outdated knowledge (drift), and communication mixes ideas across groups (gene flow). Modeling them jointly provides a quantitative framework for understanding how information arises, persists, and spreads, forming a population-level description of cultural and informational evolution.

We applied this population-genetic framework to analyze how conservation-related information accumulates and moves through policy networks. The case of grizzly bear (*Ursus arctos horribilis*) management in the Greater Yellowstone Ecosystem (GYE) provides an ideal example because it represents one of the longest-running conservation controversies in North America. Listed under the U.S. Endangered Species Act in 1975, the GYE population's recovery and repeated delisting attempts have generated decades of scientific debate, legal rulings, and political negotiation (Shafer 2022, 2025; Suzuki and Parker 2019; Fish and Wildlife Service

2017, 2007). This extensive policy history allows us to observe how scientific, legal, and social narratives evolve among actors specifically government agencies, legislators, journalists, and non-governmental organizations. Using a time-ordered corpus of documents, we quantified informational turnover by estimating rates of topic appearance and loss—analogue to mutation and drift—and evaluated their net balance over time (Mollett et al. 2025). We also assessed directional diffusion by estimating pairwise information transfer among actor groups, using an island-model migration framework to capture the fraction of discourse exchanged between them. Collectively, these analyses reveal when and where information accumulated, which topics drove those changes, and which actor groups consistently served as sources or sinks of conservation discourse across management phases in the GYE.

### **Materials and Methods**

Using our informational content quantification theory, we consider how particular themes (e.g. human wildlife conflict) related to grizzly bear conservation change and were shared across political actors over time. We relied on a previously collated dataset that collated themes of discourse from political actors in the Greater Yellowstone Ecosystem, including information from policy documents, court decisions, and news articles published between 1/1/1981 and 09/05/2024 (Mollett et al. 2025). Briefly, four search terms were used to search the U.S. News Stream ProQuest Database: 1. “Grizzly bear” AND “Greater Yellowstone Ecosystem” 2. “Grizzly bear” AND “delist” 3. “Grizzly bear” AND “Endangered Species Act” 4. “Grizzly bear state management act.” After filtering to articles focused on grizzly bears in the U.S., quotes from actors were pulled from each article and associated with one of eight conservation-related themes. Here, we focus on four of those thematic clusters: the state of grizzly bear conservation science, grizzly bear recovery goals, laws and regulations surrounding grizzly bear protection,

and human-wildlife conflict. To begin, we initially interpreted the entire corpus of articles as representing a population, and we interpreted the three themes as analogs to genetic loci, where the themes can evolve independently from each other over time.

Within each thematic area, we evaluated political actor quotes to determine the number and content of all possible informational variants, which we treated as alleles within a thematic locus. First, we tokenized all quotes within a theme, removing punctuation, numbers, symbols, and English stop words. We then extracted candidate multi-word expressions using the `textstat_collocations` function in the `quanteda.textstats` package (Benoit et al. 2020). These candidate collocations were restricted to bigrams and trigrams (two- and three-word sequences) with a minimum count of five occurrences in the theme corpus. For each candidate collocation, we computed a likelihood-ratio statistic that compared the likelihood that the tokenized words occur independently of one another to the likelihood that the words form a dependent multi-word unit. Collocations with higher likelihood ratio values occur together significantly more often than expected by chance. We then curated these statistically identified phrases by hand, merging synonymous expressions into broader categories that we defined as topics. For example, in the State of Science thematic locus, collocations such as sound science, best available science, and available science were merged into a single topic, capturing information about the credibility of evidence. In the Human-wildlife conflict theme, property damage and injury/death were merged into a topic capturing the impacts of grizzlies on people and property. The result of this process was a set of dictionaries for each theme, where each topic was defined by a set of synonymous or closely related collocations. We then applied these dictionaries back to the corpus to count the presence/absence of topics within each quote. This procedure is directly analogous to allele identification in population genetics, where methodological decisions are required to define

genetic variants that are recognized as alleles (e.g. SNPs vs. haplotypes, grouping synonymous codons).

Within our analyses, we explicitly sought to evaluate how information content and topic frequencies changed over time. Because coverage in our dataset was not evenly distributed across years and because management of grizzly bears in the Greater Yellowstone Ecosystem has proceeded in phases, we divided the publication years into time bins that reflect key events in population management and policy. This approach is directly analogous to analyzing allele frequency change across discrete generations in a biological population. (For future datasets with more even coverage, continuous year or finer-scale temporal smoothing could be used instead of bins.) Within our dataset, we considered five different time bins based on article publication year: 1. Before, < 2007, predates major delisting attempts and is the foundational grizzly recovery period; 2. During I, 2007-2010, first delisting<sup>1</sup> and subsequent reinstatement; 3. After 2011-2016, the post-reinstatement phase, characterized by renewed scientific debate, population assessments, and preparation for a second delisting attempt; 4. During II, 2017-2018, the second delisting cycle followed by another court reversal<sup>3</sup>; 5. Recent, 2019-2024, ongoing petitions, court rulings, and management discussions.

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<sup>1</sup> Under the U.S. Endangered Species Act (ESA), delisting is the removal of a species from the Federal Lists of Endangered and Threatened Wildlife and Plants when the best available scientific and commercial data show it no longer meets the ESA's definitions (e.g. due to recovery, extinction, or original data error); delisting is completed through rulemaking by the United States Fish and Wildlife Service.

<sup>2</sup> In March 2007, the U.S. Fish and Wildlife Service (USFWS) officially removed the GYE grizzly from the list of threatened species, but this decision was vacated by a U.S. District Court judge in 2009 (*Greater Yellowstone Coalition, Inc. v. Servheen*, 672).

<sup>3</sup> In June 2017, the USFWS again delisted the population, but the ruling was overturned by the District Court in 2018, restoring federal protections (*Greater Yellowstone Coalition v. Servheen*, 2018).

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To quantify how topic richness changed over time, we tracked the appearance and disappearance of dictionary-defined topics between consecutive bins, considering all actors simultaneously. For each topic within a theme, presence or absence was coded for every time bin, and this sequence of states was compared across adjacent intervals. If a topic was absent in one bin but present in the following bin, we interpreted this as a gain, directly analogous to the introduction of a new allele into a genetic population through mutation or migration. Conversely, if a topic was present in one bin but absent in the next, we interpreted this as a loss, analogous to the loss of a genetic variant through drift or extinction. In this framework, topic absence indicates that a previously active idea dropped out of public or policy discourse, effectively modeling forgetting as the disappearance of information from collective attention or communication. By summing these gains and losses across all topics within a theme, we obtained a measure of the turnover in informational content for each time step. To scale these measures to the size of the information pool, we divided the number of gains and losses by the total number of topics present in the preceding bin. These values represent per-topic rates of learning and forgetting, which we denote  $\hat{\mu}$  and  $\hat{\delta}$ , respectively. In population genetics terms,  $\hat{\mu}$  captures the probability that new alleles (topics) are added to the population between generations, while  $\hat{\delta}$  reflects the probability that alleles (topics) are lost due to random processes. Averaging these values across all transitions within a theme provided a theme-specific estimate of learning and forgetting rates. The difference between the two,  $\hat{\gamma} = \hat{\mu} - \hat{\delta}$ , reflects the net rate of change in topic richness over time, where positive values indicate overall accumulation of information and negative values indicate erosion. We then compared observed changes in allelic richness to expected changes under the constant-rate model. Starting with the observed richness in the earliest bin for each theme, we projected forward using the recursive equation

$$K_{t+1} = K_t(1 + \hat{\gamma}) \quad (7)$$

to produce an expected trajectory of information accumulation. Observed deviations from this expectation highlight periods when informational change proceeded faster or slower than predicted based on theory, suggesting either accelerated learning events, selective retention of specific ideas, or abrupt losses of previously common topics.

In addition to analyzing aggregated topic richness, we quantified the trajectory of each topic's frequency across time bins. We classified topics based on the strength and direction of their temporal correlation (Spearman's  $\rho$ ). Topics with  $\rho \geq 0.50$  were considered increasing, while those between 0.25 and 0.49 were classified as a slight increase. Similarly, topics with  $\rho \leq -0.50$  were considered decreasing, and those between -0.49 and -0.25 were classified as slight decrease. Topics with  $-0.25 < \rho < 0.25$  were treated as constant (no directional change). This allowed us to distinguish topics that contributed to richness gains from those that were declining in frequency, and to identify themes dominated by directional change versus turnover of ephemeral topics.

To relate information flow among political actors to population–genetic movement of alleles among demes, we next stratified each thematic locus by actor and time bin and then quantified topic occurrence and topic information flow among actors. (We continued to interpret themes as loci and dictionary topics as alleles and treat the five different time bins as discrete generations.) Due to data availability, for this analysis we restricted our data to article text associated with Executive branch, Legislative branch, Journalist, and NGOs, as the remaining categories were too sparse to support a time by actor by theme analysis. Within each theme, actor, and time bin,

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we summarized topic presence across quotes. To describe how ideas moved between actors, we quantified the occurrence of topics that ‘spread’ from one actor to another in consecutive time points. This followed the idea of migration between populations in classic population genetics theory. For each theme, we first computed per-actor topic frequencies in each time bin (the fraction of that actor’s quotes that mentioned a given topic). Then, for each ordered actor pair, source to recipient, we asked how much of the recipient group’s topic frequency in the next time bin could be explained by the source group’s frequency in the current bin, over and above the recipient group’s own persistence. We pooled across topics and time steps to estimate a single rate of information dispersion for each theme. The resulting estimate, which was bound by 0 and 1, was interpreted as a the per-time bin information flow rate of topics from source to recipient, or the fraction of recipient group’s next-time bin topic state attributable to source group’s current-time bin state (the remainder reflects recipient group’s own carry-over). We quantified uncertainty by bootstrapping topics within each theme (resampling topics with replacement, recomputing the rate, and taking the percentile 95% confidence interval). These were interpreted alongside the number of topic–bin transitions and distinct topics contributed. All analyses were conducted in R version 4.5.0 (R Core Team 2023).

## Results

Within the four themes (human–wildlife conflict, laws focused on conservation and management, recovery goals, and the state of the science of grizzly bear listing and delisting on the ESA), we identified several topics that served as higher-order categories of related terms. We categorized co-occurring terms into these topics and identified 22 unique topics across all themes. This included six in the human–wildlife conflict theme, five in conservation laws, five in recovery goals, and six in state of science (Table 1).

**Table 1.** Themes and topics identified in the grizzly bear (*Ursus arctos horribilis*) published articles corpus. Spearman rank correlations ( $\rho$ ) describing changes in topic frequencies across time bins for four thematic areas of grizzly bear conservation discourse. Values shown include  $\rho$ , topic start and end frequencies (proportion of quotes containing the topic in the first vs. last time bin), and the resulting trend classification (increase, slight increase, slight decrease, decrease, or constant).

Theme and topic	Change over time (Spearman rho)	Topic start and end frequency	Trend category
Human-wildlife conflict			
agencies and institutions	0.70*	0.07, 0.14	increase
climate stressors	0.00	0.00, 0.01	constant
conflict impacts on people and property	0.21	0.04, 0.06	constant
conflict mitigation and management	0.50*	0.03, 0.06	increase
geographic and ecosystem context	0.10	0.10, 0.13	constant
hunting and recreation conflicts	0.56*	0.01, 0.02	increase
Laws and regulations			
geographic contexts	0.40	0.23, 0.36	slight increase
institutions and processes	0.71*	0.00, 0.04	increase
political figures	0.30	0.12, 0.14	slight increase
species ecology in law	0.00	0.04, 0.03	constant
statutory and legal references	0.00	0.02, 0.02	constant
Recovery goals			
agency leadership and actors	-0.20	0.07, 0.03	constant
agency mentions	0.00	0.09, 0.04	constant
geographic and ecosystem context	0.90*	0.15, 0.33	increase
law and politics framing	0.71*	0.00, 0.04	increase
population viability and population capacity	0.60*	0.07, 0.08	increase
State of conservation science			
advocacy and opposition	-0.30	0.09, 0.05	slight decrease
conservation science	0.67*	0.00, 0.04	increase
domain specifics	-0.15	0.07, 0.03	constant
geographic and ecosystem context	-0.60	0.21, 0.16	decrease

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ESA and legal references	0.70*	0.14, 0.19	increase
science quality frameworks	-0.15	0.02, 0.07	constant

\*Denotes an increasing trend category

Patterns of topic richness and frequency changed over time but differed across the four themes.

In the human–wildlife conflict theme, three topics remained constant, and three showed consistent increases. The mean Spearman correlation across topics was moderately positive (mean = 0.35, range 0.00–0.70; Table 1), consistent with overall stability and modest upward trends in topic frequency over time. Observed topic richness closely matched expectations under the constant-rate model; on average across time bins, the observed richness differed from the expected trajectory by about 1.5 topics (relative mean absolute deviation = 0.23), with a maximum deviation of 2.6 topics (Fig. 2).

Similarly, the conservation laws theme was relatively stable or slightly increasing, and included one topic that increased strongly over time ( $\rho = 0.71$ ; Table 1). None decreased, yielding a moderately positive mean correlation (mean = 0.32, range 0.00–0.71). Topic information content increased from 0.08 to 0.12 across time bins, and observed richness deviated only modestly from expectation, with a mean absolute deviation of 0.7 topics (relative mean absolute deviation = 0.15) and a maximum deviation of 1.3 topics (Fig. 2).

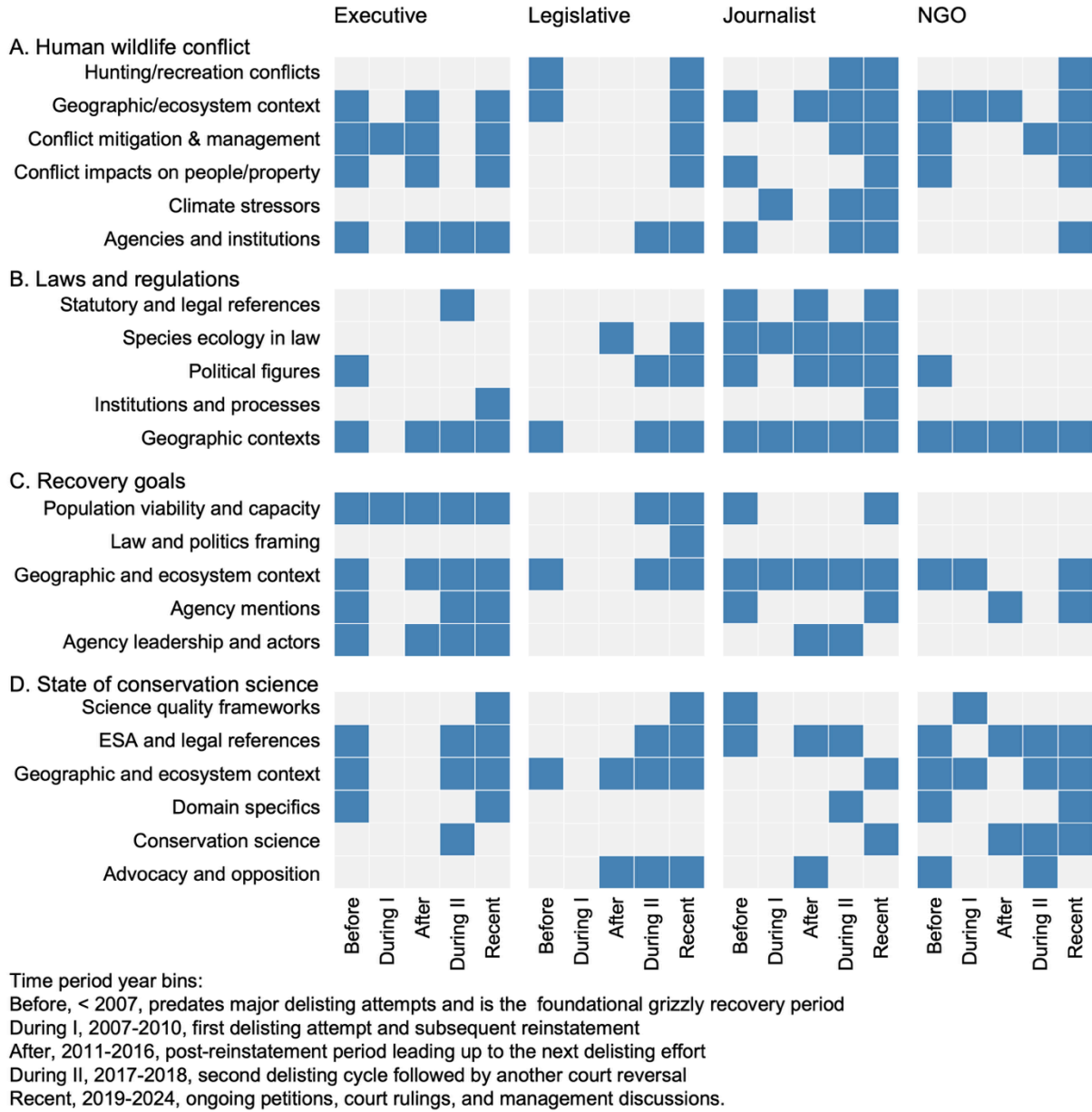
Topics in the recovery goals theme showed the most dynamic pattern. Three of five topics increased in frequency ( $\rho$  up to 0.9), and two remained constant, producing a strongly positive mean correlation overall (mean = 0.46, range –0.2 to 0.9; Table 1). Average information content rose from 0.10 to 0.14 topics, reflecting reinforcement of certain ideas over time. However, the expected trajectory predicted a much steeper increase than was realized, and deviations were

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substantial, with a mean absolute deviation of 2.0 topics (relative mean absolute deviation = 0.33) and a maximum deviation of 3.0 topics (Fig. 2). This suggests that while several topics gained in frequency, overall accumulation lagged the rate predicted by our model.

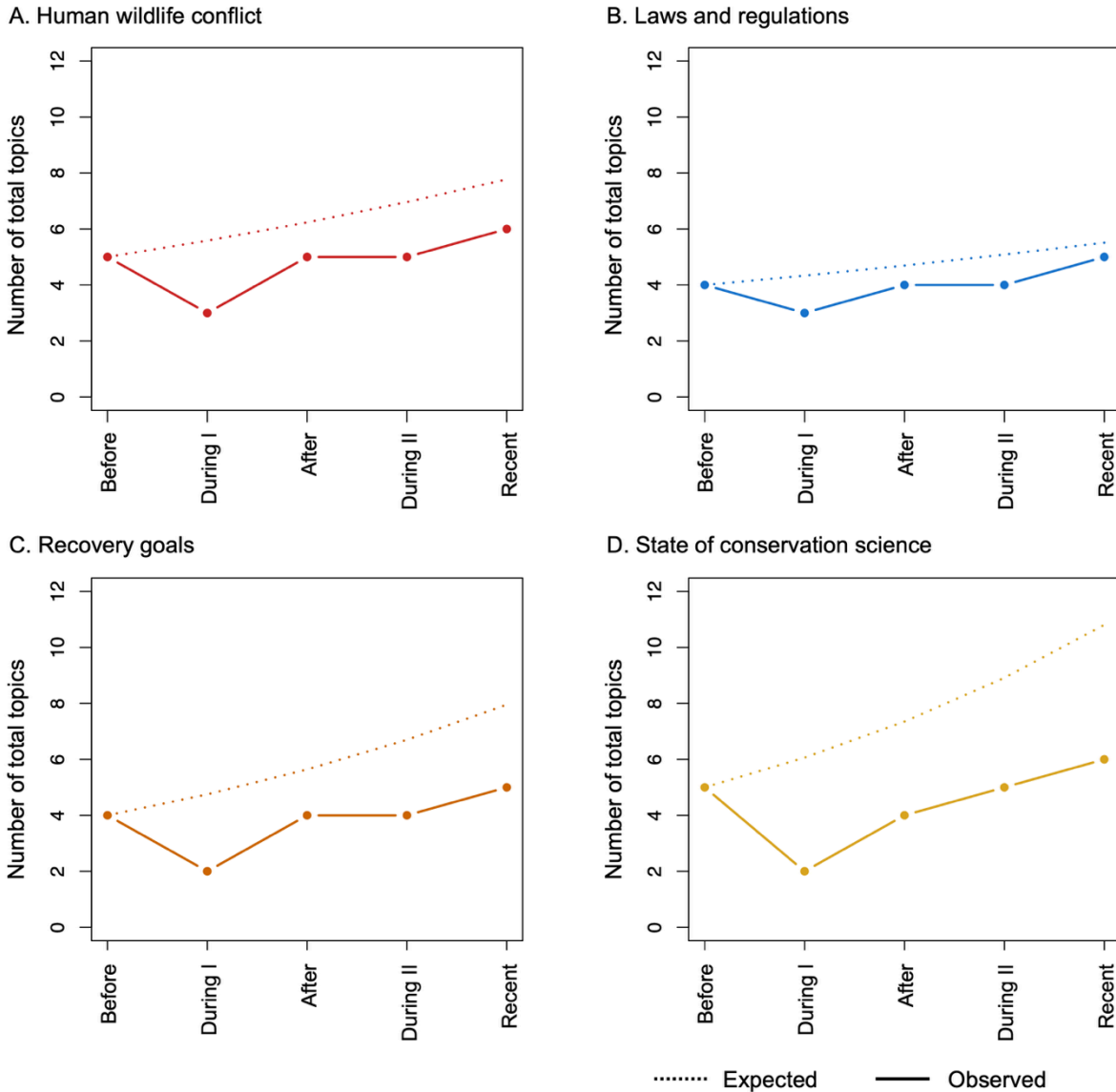
The state of conservation science theme showed a mixed outcome across topics. Overall, two topics increased ( $\rho$  up to 0.8), two decreased (as low as  $\rho = -0.6$ ), and two remained constant. The mean correlation was near zero (mean = 0.04, range  $-0.6$  to 0.8), and average information content was essentially unchanged (0.10 initially versus 0.09 in the last bin; Fig. 1). Observed richness deviated more strongly from expectation than in other themes, with a mean absolute deviation of 3.2 topics (relative mean absolute deviation = 0.40) and a maximum deviation of 4.8 topics, suggesting periods of abrupt gain or loss not captured by the constant-rate model (Fig. 2).

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**Fig. 1.** Presence of discourse topics across time within four thematic areas of grizzly bear conservation: (A) human–wildlife conflict, (B) laws and regulations, (C) recovery goals, and (D) state of conservation science. Rows represent topics within each theme, columns represent actor groups (Executive, Legislative, Journalist, and non governmental organizations--NGOs), and shading indicates whether a topic was present in a given time bin. Time bins span key periods of delisting attempts and management decisions for grizzly bears (*Ursus arctos horribilis*).

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Before, < 2007, predates major delisting attempts and is foundational grizzly recovery period  
 During I, 2007-2010, first delisting attempt and subsequent reinstatement  
 After I, 2011-2016, post-reinstatement period leading up to the next delisting effort  
 During II, 2017-2018, second delisting cycle followed by another court reversal  
 Recent, 2019-2024, ongoing petitions, court rulings, and management discussions.

**Fig. 2.** Temporal dynamics of discourse topics across actor groups. Number of distinct topics within each thematic cluster across five historical periods of grizzly bear management. Panels show (A) human–wildlife conflict, (B) laws and regulations, (C) recovery goals, and (D) state of conservation science. Solid lines indicate observed patterns from the discourse data, while dashed lines indicate expected values under the theoretical model. Divergence between observed and expected lines reflects periods where actor groups used more (or fewer) topics than predicted by theory, highlighting shifts in the flow and breadth of conservation discourse.

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We found that topic migration rates inferred from changes in actor-level frequencies varied across themes, with the strongest and most reliable transitions occurring in human–wildlife conflict and state of conservation science discourse. The topic migration rate was an inferred probability of a topic’s first occurrence in one actor type being followed by its appearance in another. Within the human–wildlife conflict theme, the executive branch and journalists played central roles in shaping subsequent discourse by the legislature (Supplementary Table 1). Executive use of conflict topics strongly predicted legislative uptake (information flow rate = 0.78, 95% CI: 0.42–0.96, 11 transitions), and journalists also influenced legislatures at nearly the same rate (information flow rate = 0.77, 0.43–1.00, 11 transitions; Supplemental Figure 1). NGOs contributed substantially to journalists’ use of conflict topics (information flow rate = 0.79, 0.30–1.00, 12 transitions), while executives influenced journalists at a more moderate yet substantial (information flow rate = 0.52, 0.32–0.79, 15 transitions). These results indicate that conflict narratives were broadly shared, with executives, journalists, and NGOs serving as key sources of information that spread to legislatures and across sectors.

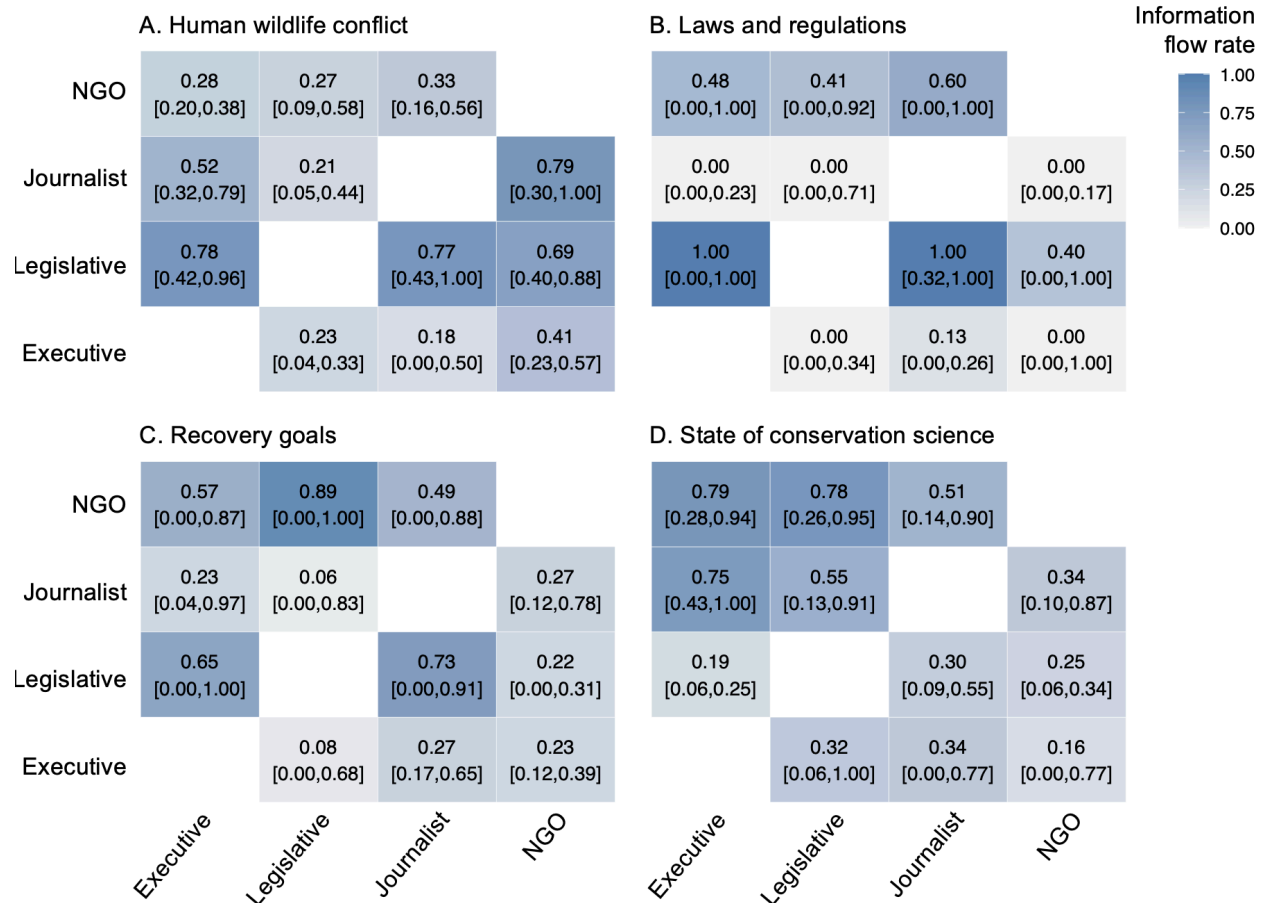
In contrast, discourse surrounding laws and regulations as well as recovery goal themes were more uncertain. The strongest uptake occurred from journalists to legislatures (information flow rate = 1.00, 0.32–1.00, 13 transitions; Supplemental Figure 1), indicating that legislative framing of legal issues often followed media coverage. Other apparent high rates, such as executives to legislatures, were based on few transitions and wide confidence intervals, limiting confidence in those estimates. In the recovery-goal theme, executives appeared to influence legislatures (information flow rate = 0.65, 0.00–1.00, 12 transitions) and NGOs (information flow rate = 0.57, 0.00–0.87, 14 transitions), and journalists influenced legislatures at a moderate rate (information flow rate = 0.73, 0.00–0.91, 9 transitions; Supplemental Figure 1). However, the wide confidence

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intervals and relatively small numbers of transitions suggest that recovery goals circulated less consistently among actors compared to other themes.

The state of conservation science theme displayed the most widespread and consistent exchange. Executives influenced both NGOs (information flow rate =0.79, 0.28–0.94, 12 transitions) and journalists (information flow rate =0.75, 0.43–1.00, 10 transitions), while legislatures also strongly influenced NGOs (information flow rate =0.78, 0.26–0.95, 12 transitions; Supplemental Figure 1). Journalists contributed to NGO uptake as well (information flow rate =0.51, 0.14–0.90, 14 transitions). These results suggest that scientific discourse was broadly disseminated across actors, with government and media groups alike serving as sources for NGO engagement. Taken together, these findings highlight that the most consistent pathways of information flow occurred from executives and journalists to legislatures in the domains of conflict and law, and from both executives and legislatures to NGOs in science-related discourse. In contrast, recovery-goal discourse showed weaker and less directional exchange.

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**Fig. 3.** Pairwise information flow rates among actor groups across thematic clusters. Estimated rates describe the fraction of topic use in one actor group at time  $t+1$  attributable to the discourse of another group at time  $t$ , following an island-model analogy from population genetics. Panels show results for (A) human–wildlife conflict, (B) laws and regulations, (C) recovery goals, and (D) state of conservation science. Estimates are pooled across topics and time steps within each theme and uncertainty is reflected in the 95% bootstrap confidence intervals computed by resampling topics. Higher values indicate stronger directional flow of information between actors, while lower values indicate greater self-retention or limited exchange.

## Discussion

Our analytical framework provides a broadly generalizable method for quantifying how information arises, persists, and spreads, extending beyond the realm of conservation governance. By modeling discrete units of information as analogous to genetic variants, this approach can be applied to any system in which ideas, behaviors, or cues diffuse through

communities. The potential applications span multiple fields, including public-health communication (Van Bavel et al. 2020), sociopolitical belief formation (van der Linden et al. 2015), and animal cultural transmission, such as chimpanzee tool use or whale song dialects (Garland et al. 2017; Whiten et al. 2011). Few existing approaches in these domains provide a quantitative way to measure directional flow, turnover, and exchange rates of information with the rigor that population-genetic models allow. By filling that gap, our method creates new opportunities for studying information evolution in both human and nonhuman societies.

Having established its broader relevance, we use grizzly bear governance in the Greater Yellowstone Ecosystem as a case study to demonstrate how this framework operates in practice. Here, applying population-genetic principles allowed us to estimate rates of information transmission and exchange among actors, paralleling models of allele migration among populations. This quantitative analogy offers a structured way to describe how discourse evolves, which is a valuable contribution in a field where communication is central, yet where no widely adopted theoretical framework exists for understanding how ideas move among diverse groups involved in conservation decision making. Existing scholarship often borrows concepts from social learning, social networks, or even memetics to describe how information circulates, but these approaches rarely provide a directional account of how discourse moves between groups over time (Mahajan et al. 2021; Wineland and Neeson 2022). Our findings address that gap by providing a replicable, mathematically grounded approach for tracing information diffusion within conservation governance systems.

Our findings show clear parallels with established patterns of policy diffusion. In the human-wildlife conflict and laws and regulations themes, journalists and executives often acted

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as sources of discourse that later appeared in legislatures, consistent with diffusion through learning (Shipan and Volden 2008). For example, legislators appear to have adopted frames after observing them in media or executive statements. In the state of conservation science, both executives and legislatures strongly influenced NGOs, suggesting a form of authority-driven diffusion, where information flowed from institutions with formal decision-making power to civil society actors (Graham et al. 2013). At the same time, information from NGOs or journalists that flowed back into government groups, though weaker, highlights that horizontal diffusion can also occur, akin to the peer-to-peer adoption observed in policy innovation studies (Berry and Berry 1990). These patterns align with diffusion mechanisms identified in political science, including learning, imitation, and authority, and demonstrate that conservation discourse follows structured and interpretable pathways of transmission rather than spreading randomly (Gilardi 2010).

The theme-specific nature of these flows suggests that the mechanisms underlying diffusion vary with issue context. Conflict-related and legal themes were characterized by strong flows into legislatures, underscoring how decision-making bodies may rely on cues from executives and the media when interpreting contentious or politically salient issues. In contrast, discourse on recovery goals circulated less consistently among groups, with wide confidence intervals and fewer transitions, implying that such discussions may remain more localized or fragmented. By comparison, discourse around the state of conservation science displayed multiple strong and reciprocal flows, particularly from governmental actors into NGOs, indicating that scientific information may diffuse more broadly across institutional boundaries. These differences mirror findings in policy diffusion research, where some policies spread rapidly and widely through learning and imitation, while others diffuse more slowly or remain confined to certain

jurisdictions. Our theme-specific flows align with policy diffusion research showing that mechanisms vary by issue context. High-salience, highly visible issues that draw a lot of attention, and conflictual topics tend to spread via elite cue-taking and authority signals, whereas technical or goal-setting issues (such as genetics considerations in delisting) diffuse more unevenly through localized learning and professional networks (Gilardi 2010).

While our analysis provides new insights into how conservation discourse spreads, several limitations warrant consideration. Unlike cross-national policy diffusion, where governments operate as independent units, the actors examined here are embedded within the same governance system, which may intensify interactions or constrain independence in ways not captured by traditional diffusion models. Our estimates are also shaped by the temporal resolution of the data; binning quotes by period necessarily smooths finer-grained dynamics of uptake, and event counts were modest for some actor pairs, leading to wide confidence intervals. Finally, our focus on a single case study, the Greater Yellowstone Ecosystem, limits generalization, as diffusion pathways may differ in other ecological or political contexts. Future work should test whether similar dynamics emerge in other conservation controversies and explore how network position, institutional authority, and thematic salience interact to shape the speed and direction of discourse diffusion.

By framing conservation discourse through the lens of policy diffusion, our study contributes to the development of a more formal theoretical foundation for understanding how ideas move within conservation governance (Graham et al. 2013). Whereas conservation research has often described communication patterns in descriptive or case-specific terms (Tews et al. 2003), our approach leverages population genetics theory to provide a quantitative model of how

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information arises, persists, and flows among actors. This gives us a set of population-level statistics, analogous to genetic topics of migration and drift, that capture the dynamics of discourse exchange. To interpret these quantitative patterns, we draw on insights from policy diffusion theory, which identifies mechanisms such as learning, imitation, authority, and competition as drivers of idea spread (Berry and Berry 1990; Dobbin et al. 2007). In this way, population genetics provides the mathematical framework for measuring information dynamics, while policy diffusion offers the conceptual categories for explaining why particular pathways dominate. Together, they extend tools from both biology and political science to conservation, a domain where coordinated action often depends on aligning perspectives across diverse institutions and sectors.

Recognizing these diffusion pathways has important implications for conservation policy and advocacy. The strong influence of journalists and executives on legislative discourse suggests that strategic engagement with media and executive offices may be particularly effective for shaping how conservation issues enter formal decision-making arenas. Similarly, the consistent flow of scientific themes from governmental actors to NGOs highlights the potential for leveraging institutional authority to build broader civil society support for science-based management (Gray 2016; Posner et al. 2016). Conversely, the weaker and less consistent flows in recovery-goal discourse suggest that advocates may need to employ more targeted strategies to ensure these messages are taken up across groups. By aligning communication strategies with the empirically observed diffusion dynamics, conservation practitioners and policymakers can better anticipate which actors are most likely to serve as effective conduits for disseminating information and advancing coordinated action (Ernstson et al. 2010).

### **Acknowledgements**

We thank S. Ditchkoff, R. Gitzen, S. Zhody, and members of the Willoughby lab for constructive comments on earlier versions of this manuscript. This project was supported in part by the National Science Foundation (2408907 to KHD and JRW) and the Alabama Agricultural Experiment Station of the USDA National Institute of Food and Agriculture (Hatch project 1025651, JRW). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

### **Data availability**

The figure and analysis code are available via GitHub at <https://github.com/andreamiranda26/PopGenInfo>.

### **Conflict of interest**

The authors declare that they have no competing interests.

### **Author contributions**

J.R.W., K.H.D., and A.M.P. conceived the ideas and designed the methodology; J.R.W., and A.M.P. collected and analysed the data and led the writing of the manuscript. J.R.W., K.H.D., B.J.S., K.M.C., and A.M.P. revised and contributed critically to the drafts and gave final approval for publication.

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