ARTICLE

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Researcher effects on the biological structure and edaphic conditions of field sites and implications for management

Shelby A. Rinehart[1,2] ⓘ | **Jacob M. Dybiec**[2†] | **Parker Richardson**[3,4] |
Janet B. Walker[3,4,5] | **James D. Peabody**[6] | **Julia A. Cherry**[2,7]

[1]Department of Biodiversity, Earth and Environmental Science, Drexel University, Philadelphia, Pennsylvania, USA

[2]Department of Biological Sciences, University of Alabama, Tuscaloosa, Alabama, USA

[3]Department of Biology, San Diego State University, San Diego, California, USA

[4]Coastal and Marine Institute, San Diego State University, San Diego, California, USA

[5]Biology Department, Southern California Coastal Water Research Project, Costa Mesa, California, USA

[6]Department of Psychological Sciences, Texas Tech University, Lubbock, Texas, USA

[7]New College, University of Alabama, Tuscaloosa, Alabama, USA

Correspondence
Julia A. Cherry
Email: cherr002@ua.edu

Funding information
University of Alabama

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Abstract

Field studies are necessary for understanding natural processes in spite of the human-induced disturbances they cause. While researchers acknowledge these effects, no studies have empirically tested the direct (e.g., harvesting plants) and indirect (i.e., trampling) effects of researcher activities on biological structure and edaphic conditions. We leveraged field studies in Alabama and California to monitor the recovery of tidal marshes following research activities. Researcher effects on animals, plants, and sediment conditions remained prevalent almost one year after the disturbance ended. For instance, trampled plots had 14%–97% lower plant cover than undisturbed plots after >10 months of recovery. Researcher effects also impacted plant composition, leading to increased subordinate species abundance. We encourage field researchers to adopt strategies that reduce their scientific footprints, including reducing field visits, limiting field team size, and considering ways to limit potential environmental impacts during study design.

KEYWORDS
disturbance, ecological memory, manipulative studies, sustainable science, tidal marsh, trampling, wetland management

Shelby A. Rinehart, Jacob M. Dybiec, Parker Richardson, and Janet B. Walker contributed equally to the work reported here.

† Deceased.

INTRODUCTION

Experimental and observational field studies are essential tools for developing ecological theories that describe the processes governing ecosystem structure and functions. For instance, field studies implemented at various spatial and temporal scales have helped develop island biogeography theory (Simberloff, 1974; Simberloff & Wilson, 1970), the resource ratio hypothesis (e.g., The Park Grass experiment; Silvertown et al., 2006; Tilman, 1982), the keystone species concept (Paine, 1966), theories of species interactions (Connell, 1961; Estes & Palmisano, 1974), and models of ecosystem disturbance (e.g., Hubbard Brook Ecosystem Study; Holmes & Likens, 2016). Despite field studies being critical tools to advance scientific understanding, as a community of field researchers, we would be remiss if we did not recognize that conducting field research can disturb and degrade important habitats and the species that inhabit them (Bryzek et al., 2022). Here, we evaluate the effects of researchers following a series of manipulative field experiments to better understand the impacts of field research and develop practices to mitigate these impacts.

Field researchers can disturb ecosystems through direct (i.e., scientific activities) and indirect (e.g., unintentional activities) pathways. The direct effects of researchers come in two key forms. First, sample collection can disturb various components of the environment. Collecting and interacting with wild animals can have adverse effects on their populations and behaviors (China et al., 2021; Ikin, 2011; Lewis et al., 2022). For instance, reduced human activity during the COVID-19 lockdowns led to increased abundance of important fish species (e.g., *Siganus argenteus*, *Scolopsis ghanam*) on shallow coral reefs along the northern Gulf of Aqaba (China et al., 2021). Additionally, harvesting plants can defoliate habitat, alter plant community composition, and impact nutrient processing rates (Hille et al., 2018; Jabłońska et al., 2021). Soil coring and soil pits may also adversely affect environmental processes. Specifically, coring sediments and soils may be analogous to animal burrowing, increasing sediment homogenization and oxygenation (Bertness, 1985; Bortolus & Iribarne, 1999; Kristensen & Alongi, 2006; Rinehart, Dybiec, Mortazavi, et al., 2023).

Second, planned manipulations of environmental attributes during field experiments, while designed to test specific hypotheses, may create legacy effects (intentional and unintentional) on local biological structure and ecosystem functions that can last beyond the life of the study. For example, David Simberloff and E.O. Wilson conducted a study wherein they fumigated entire mangrove islands along the Florida Keys with methyl bromide to remove all arthropod fauna so they could monitor island recolonization (Simberloff & Wilson, 1969, 1970). This study led to rapid mangrove damage (i.e., 5%–100% of leaves were burnt; Wilson & Simberloff, 1969), a decline in arthropod abundance that lasted over 250 days (Simberloff & Wilson, 1969), and a shift in arthropod community composition that lasted at least two years (Simberloff & Wilson, 1970). Similarly, Deegan et al. (2012) enriched ~30,000 m² of tidal marsh in the Plum Island Estuary in Massachusetts with nitrogen and phosphorus over a nine-year period to test the effects of eutrophication on coastal ecosystems. Their manipulation resulted in decreased belowground productivity, higher rates of creek-bank collapse, and the conversion of vegetated marsh into unvegetated mud flats, all of which can degrade tidal marsh ecosystem services (e.g., carbon sequestration and nitrogen removal; Craft et al., 2009; Deegan et al., 2012; Hinshaw et al., 2017). While most experimental manipulations have considerably smaller spatial and temporal impacts than Simberloff and Wilson (1969) and Deegan et al. (2012), it is still important to consider the consequences of field manipulations for biological structure and ecosystem functions.

Researcher indirect effects occur when researchers impact the environment through activities such as trampling. Human trampling can affect the physiology and morphology of vegetation (Goldman Martone & Wasson, 2008; Kuss & Graefe, 1985), subterranean fauna (Chappell et al., 1971), and edaphic conditions (Pescott & Stewart, 2014; Ros et al., 2004). Additionally, the impacts of human trampling on vegetation depend on the specific traits (e.g., life forms) of the plant populations and communities (Pescott & Stewart, 2014). For instance, habitats dominated by grasses (e.g., *Festuca* spp.) have been shown to be less susceptible to the impacts of human trampling than habitats dominated by deciduous shrubs (e.g., *Symphoricarpos* spp.) and herbaceous perennial plants (e.g., *Clintonia* spp.; Cole, 1987). Thus, broadly evaluating the impacts of researcher trampling on plants requires considering the variation in plant traits observed across ecological communities.

Despite the clear pathways by which researcher activities (direct and indirect) may impact the environment, to our knowledge, there have been no attempts to quantify the direct and indirect effects of researcher disturbance in ecological systems. This gap is surprising given that (1) various field researcher communities (e.g., hydrothermal vent researchers) have implemented codes of conduct to limit researcher impacts (Devey et al., 2007; Godet et al., 2011; Van Dover, 2012; Van Dover et al., 2012), (2) several federal and state agencies (e.g., National Estuarine Research Reserves) install boardwalks to minimize researcher impacts, and

(3) similar human activities (e.g., recreational habitat trampling) have well-documented negative effects across habitats (Cole, 1987, 1995; Leung et al., 2000; Pescott & Stewart, 2014). Thus, empirically testing how researcher effects (direct and indirect) influence the environment will provide a critical first step in developing a framework for implementing ethical and sustainable field practices.

Here, we evaluated the direct and indirect effects of researchers in natural and constructed tidal marshes along the Alabama and southern California coastlines. Specifically, we monitored the recovery of animal populations, plant communities, and sediment conditions for approximately one year in areas that were previously (1) manipulated and sampled (e.g., defoliated) and (2) impacted by researcher trampling. We predicted that researcher indirect effects would be greater than direct effects in all ecosystems. Additionally, we anticipated that researcher effects would be more pronounced in constructed marshes than in natural marshes because constructed systems lack the material and informational legacies necessary for rapid recovery following disturbance (Johnstone et al., 2016). Understanding how researcher activities impact ecosystems with different natural histories (e.g., natural vs. constructed) in distinct North American ecoregions will help inform predictions of when and where researchers have detrimental effects on the environments they study and hopefully lead to the development and implementation of ethical practices to mitigate those impacts.

METHODS

Conceptual approach

In 2018 and 2021, we completed caging studies manipulating burrowing crab communities in tidal marshes in two regions—southern California (CA) and Alabama (AL), respectively (Walker, Grosholz, & Long, 2021; Walker, Rinehart, et al., 2021; Appendix S1). Both studies involved manipulating crab population densities using cages (i.e., high crab and low crab burrow densities), harvesting aboveground plant biomass (CA: 0.7 × 0.7 m, length × width; AL: 0.5 × 0.5 m), coring sediments (CA: 50 × 50 × 27 cm, length × width × depth; AL: 18 × 10 cm, diameter × depth), and severing plant rhizomes (CA: 30-cm depth; AL: 15-cm depth; Appendix S1). High crab plots in both regions contained ambient burrowing crab densities (based on crab burrow densities) and low crab plots had reduced burrowing crab densities (see Appendix S1).

Maintaining and sampling these experimental manipulations resulted in habitat trampling. Following our direct (i.e., manipulations and sampling) and indirect (i.e., trampling) effects on tidal marshes in AL and CA, we monitored the recovery of crab populations, plant community structure, and edaphic conditions (AL only) through the following growing season in each marsh site. To minimize the environmental impacts of our continued monitoring, we (1) stayed on established trails, (2) reduced team sizes (1–2 researchers per visit), and (3) decreased our site visits to every other month.

Site descriptions

In both regions, we used two tidal marsh sites. Each region had one natural tidal marsh and one constructed tidal marsh (AL: 34 years old; CA: ~17 years old).

Alabama

Our natural site was Fowl River Natural Marsh (AL-NAT; 30°22′02.5″ N, 88°09′37.2″ W) and our constructed site was Fowl River Constructed Marsh 1 (AL-CON; 30°22′02.3″ N, 88°09′06.8″ W). AL-CON was initially constructed in 1987 by harvesting pine savanna habitat and excavating topsoil down to a clay layer that intercepted the water table and was 0.27 m above mean sea level (NAVD88 datum). AL-CON and AL-NAT are separated by an approximately 0.5-km thick pine savanna and have distinct hydrodynamics and biological structure (Dybiec et al., 2023; Ledford et al., 2021; Rinehart, Dybiec, Mortazavi, et al., 2023; Tatariw et al., 2021). The site was then planted with needlerush (*Juncus roemerianus*) and smooth cordgrass (*Spartina alterniflora*) in 1988 (Vittor et al., 1987). Today, both AL sites are almost entirely dominated by needlerush (Ledford et al., 2021; Rinehart, Dybiec, Mortazavi, et al., 2023; Tatariw et al., 2021), although the subordinate species, *Distichlis spicata*, is also common at AL-NAT. Burrowing crabs, fiddler crabs (i.e., *Minuca longisignalis*, *Minuca minax*, *Leptuca panacea*, and *Leptuca spinicarpa*), and marsh crabs (*Sesarma reticulatum*) are common and have known effects on needlerush productivity and sediment conditions (Rinehart, Dybiec, Mortazavi, et al., 2023).

Southern California

Our natural site was Kendall-Frost Marsh (CA-NAT; 32°47041.0″ N, 117°13046.4″ W) and our constructed site was San Dieguito Lagoon (CA-CON; 32°58047.0″ N,

117°14043.6″ W). CA-CON was initially constructed in 2006 and planted with Pacific cordgrass (*Spartina foliosa*) and pickleweed (*Sarcocornia pacifica*) in 2008, with subsequent grading and planting activities occurring from 2009 to 2022 (Beheshti et al., 2022, 2023). At both sites, Pacific cordgrass dominates low-elevation habitat, pickleweed dominates high-elevation habitat, and mixtures of these species occur at intermediate elevations (Walker et al., 2022; Walker, Rinehart, et al., 2021). Subordinate plants are more common at CA-NAT and include *Salicornia bigelovii*, *Jaumea carnosa*, *Batis maritima*, and *Triglochin maritima*. Burrowing crabs, including lined shore crabs (*Pachygrapsus crassipes*) and Mexican fiddler crabs (*Leptuca crenulata*), are abundant at CA-NAT and CA-CON and can influence plant community structure and edaphic conditions (Walker, Grosholz, & Long, 2021; Walker, Rinehart, et al., 2021).

Experimental design

The study included four treatments: High Crab, Low Crab, Trampled, and Control ($n = 5$ treatment^{-1}) at constructed and natural marshes in both regions. The High Crab and Low Crab treatments were established in the exact locations of the high-crab density and low-crab density cages, respectively, that were part of the original burrowing crab manipulative studies conducted at each site (Appendix S1). Thus, these plots had their crab communities modified, aboveground biomass harvested, rhizomes severed, and sediments cored as part of prior experiments (Appendix S1). Trampled plots were established outside of the original cages, but in areas where researchers frequently had to walk to maintain the original caging studies. Controls were placed in a nearby habitat that was previously undisturbed by researcher activities. Plot sizes were 0.7×0.7 m (length × width) in CA and 0.5×0.5 m in AL.

Starting in February (AL: 2021; CA: 2019), we monitored crab burrow density, plant cover, and the mean height and stem density (AL: $n \leq 5$ stems plot^{-1}; CA: $n \leq 10$ stems plot^{-1}) of the dominant plant species (AL: needlerush; CA: Pacific cordgrass) in each marsh every other month until September (CA) and October (AL). Additionally, in October in AL marshes, we collected one, 10-cm-deep sediment core using a Russian Peat corer (inner diameter [ID] = 5 cm) that we subsectioned in the field at 2.5-cm intervals. Subsections were oven-dried at 60°C to a constant mass to obtain bulk density, and once dried, samples were ground with a mortar and pestle before being ashed in a muffle

furnace (6 h at 550°C) to estimate sediment organic matter (SOM) via loss on ignition. We also collected one, 10-cm-deep sediment core using a t-corer (ID = 7.9 cm) that we subsectioned in the field at 5-cm intervals to assess belowground biomass at the AL sites. Subsections were rinsed to remove sediment attached to belowground biomass, which was then dried at 60°C to a constant mass (Conner & Cherry, 2013).

Data analysis

We used separate two-factor ANOVAs for each region (i.e., AL and CA) to evaluate the effects of researcher impacts (i.e., experimental manipulations and trampling) on tidal wetland burrowing crab populations, plant communities, and edaphic conditions in each region. However, we were unable to evaluate crab burrow density at AL-CON due to tidal inundation. Because of this, we modified our analysis and ran a one-factor ANOVA for burrowing crab density between researcher impact treatments at AL-NAT. All models included Treatment and Marsh Type (i.e., NAT and CON) as fixed factors. We ran separate models for each region because the studies were conducted in different years and have distinct plant communities. If model assumptions were violated, we transformed the data. We used Tukey's honestly significant difference (HSD) tests ($\alpha = 0.05$) when significant variables were detected. We used measurements taken at the end of each region's growing season (AL = October; CA = September) in all ANOVAs; thus, time was not a factor in any of our models. All temporal data are available in Rinehart, Dybiec, Richardson, et al. (2023).

We also used separate two-factor ANOVAs for each AL marsh type (i.e., NAT and CON) to assess the effects of the experimental manipulations on belowground biomass, sediment bulk density, and SOM at the end of the growing season (October) in AL. We ran separate models for each AL site because we knew that AL-CON had less belowground plant biomass, higher sediment bulk density, and lower SOM content than AL-NAT (Ledford et al., 2021; Rinehart, Dybiec, Mortazavi, et al., 2023; Tatariw et al., 2021). Thus, models included treatment and sediment depth as fixed factors. Tukey's HSD tests ($\alpha = 0.05$) were used as needed. All models were conducted with the "aov" function in R software v. 4.0.2 (Kassambara, 2023; R Core Team, 2020).

We compared the effects of experimental manipulations and trampling across regions by estimating the log response ratio (LRR; mean $\pm$ 1 var) effect size in OpenMEE (Wallace et al., 2017). LRRs were calculated using the High Crab, Low Crab, and Trampled treatments as experimental

groups and the Control treatment as the control group (Hedges et al., 1999; Lajeunesse, 2011). We calculated LRRs for all crab population, plant community, and edaphic condition metrics. Specifically, with plant community response variables, we calculated LRRs for the stem height and stem density of the dominant plant species in each region (i.e., needlerush in AL and Pacific cordgrass in CA). Negative LRRs suggest researcher effects decrease the response variable relative to undisturbed controls, while positive LRRs suggest researcher effects increase the response variable relative to undisturbed controls. LRRs are presented as a forest plot. We generalized researcher impacts between sites by qualitatively comparing how the LRRs for each response variable deviated from zero.

RESULTS

Alabama

Crab populations

Crab burrow density data were only available for the first two (February and April) of the five months sampled; thus, we removed AL-CON from the analysis and ran a one-factor ANOVA with treatment as a fixed factor for crab burrow density at AL-NAT. We were also unable to collect burrow density data from one replicate of each treatment at AL-NAT in October due to tidal inundation; thus, all treatments had $n = 4$ for this analysis. Overall, researchers had no effect on crab burrow density at AL-NAT ($F = 2.23$, df $= 3$, $p = 0.138$; Appendix S3: Figure S1). However, researcher direct effect plots (High Crab, Low Crab) tended to have higher crab burrow densities than Trampled and Control plots. Additionally, LRRs suggest that researcher direct (i.e., manipulations and sampling) and indirect (i.e., trampling) effects have a slight positive effect on crab burrow density (Figure 1).

Plant communities

There was an interaction between Marsh Type and Treatment on total plant cover ($p = 0.010$; Figures 1–3; Appendix S2: Table S1; Appendix S3: Figure S2). At AL-NAT and AL-CON, all researcher impact plots (High Crab, Low Crab, and Trampled) had lower total plant cover than Control plots (Figure 3; Appendix S3: Figure S2). Additionally, Trampled plots had lower plant
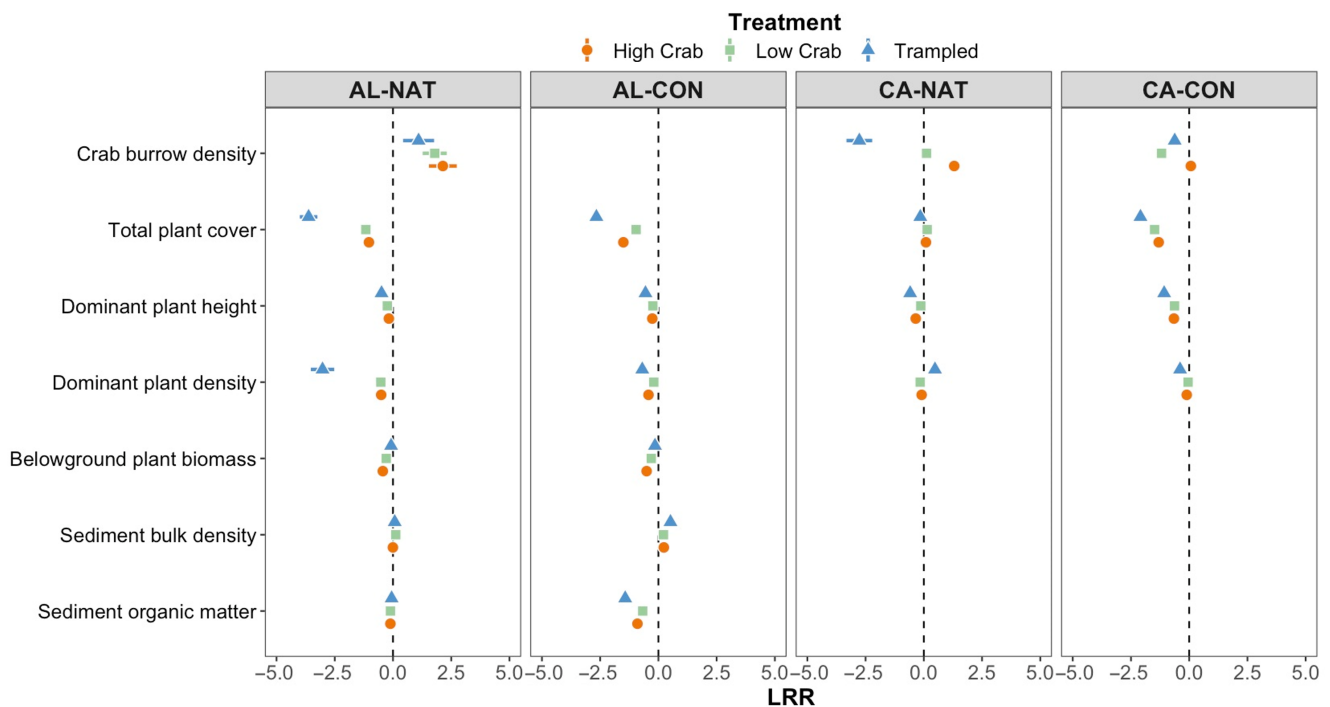
FIGURE 1 Log response ratio (LRR) effect size calculations (mean ± 1 population variance) for the impact of researcher effects treatments (i.e., High Crab, Low Crab, and Trampled) on burrowing crab populations, plant community traits, and sediment properties in four tidal marshes. High Crab treatments are denoted by orange circles, Low Crab treatments are denoted by green squares, and Trampled treatments are denoted by blue triangles. AL-NAT and AL-CON are the natural and constructed tidal marshes, respectively, in Alabama. CA-NAT and CA-CON are the natural and constructed marshes, respectively, in southern California.
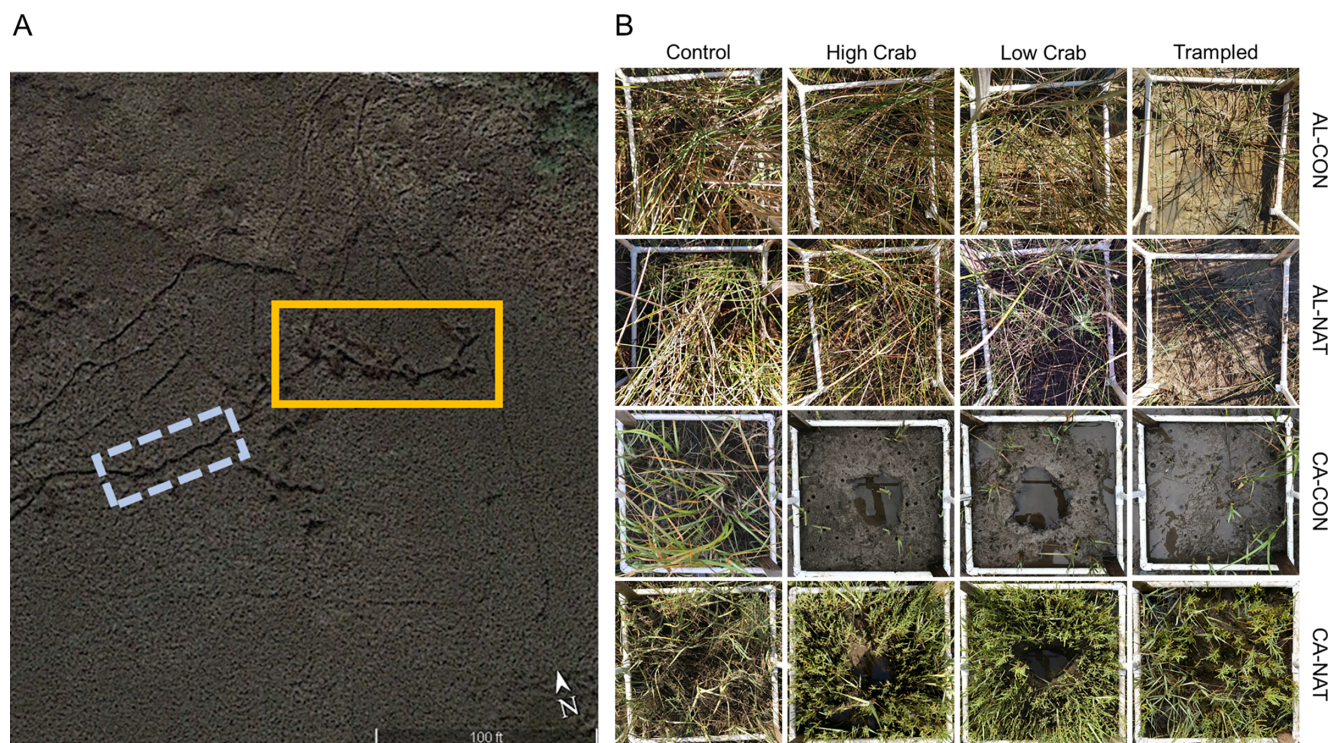
FIGURE 2 (A) Google Earth image of the Alabama natural marsh (AL-NAT) from December 2022. The blue rectangle (dashed line) denotes researcher trails caused by trampling. The yellow rectangle (solid line) denotes the footprint of the burrowing crab caging study deployed from April to December 2021 (Appendix S1). (B) Images of each treatment (i.e., Control, High Crab, Low Crab, and Trampled) at the Alabama (AL-CON, AL-NAT) and California (CA-CON, CA-NAT) marshes. Photo credits: Alabama, S. Rinehart; California, P. Richardson. Images are from October 2022 in Alabama and June 2019 in California, 10 months and 8 months, respectively, after the researcher effects occurred.

cover than High Crab and Low Crab plots at AL-NAT, and Trampled and High Crab plots had lower plant cover than Low Crab plots at AL-CON (Figure 3; Appendix S3: Figure S2). LRRs suggest that researcher direct and indirect effects have a large negative effect on total plant cover (Figure 1).

Marsh Type and Treatment interacted to affect needlerush stem density ($p = 0.005$; Figure 4; Appendix S2: Table S1). At AL-CON, needlerush stem density was similar in High Crab, Low Crab, and Control plots. However, Trampled plots had 24%–50% fewer needlerush stems than High Crab, Low Crab, and Control plots (Figure 4). At AL-NAT, High Crab, Low Crab, and Trampled plots had 40%–95% fewer needlerush stems than Control plots (Figure 4). High and Low Crab plots also had higher needlerush stem densities than Trampled plots. LRRs suggest that researcher effects have negative effects on needlerush stem density, but researcher indirect effects tend to be more detrimental than researcher direct effects (Figure 1).

Treatment affected needlerush stem height ($p < 0.001$; Figure 4B; Appendix S2: Table S1). In both marshes, stems in High Crab, Low Crab, and Trampled plots were shorter than stems in Control plots (Figure 4). Needlerush stems in

High Crab and Low Crab plots were also taller than stems in Trampled plots (Figure 4). LRRs suggest that researcher direct and indirect effects have a slight negative effect on mean needlerush stem height (Figure 1).

At AL-NAT, there was no significant effect of Treatment or Depth on plant belowground biomass. However, there was an interaction between Treatment and Depth on plant belowground biomass at AL-CON ($p = 0.034$; Appendix S2: Table S2; Appendix S3: Figure S3). Trampled plots tended to have higher belowground biomass at 0–5 cm depth than High Crab, Low Crab, and Control plots; but this effect diminished at depths of 5–10 cm (Appendix S3: Figure S3). Across all depths, LRRs suggest that the researcher indirect effects did not impact plant belowground biomass, but researcher direct effects had a slight negative effect on plant belowground biomass in both marshes (Figure 1).

Sediment characteristics

Bulk density increased with depth at both marshes (AL-NAT: $p < 0.001$; AL-CON: $p = 0.018$; Figure 5; Appendix S2: Table S2). Researcher effects (Treatment)
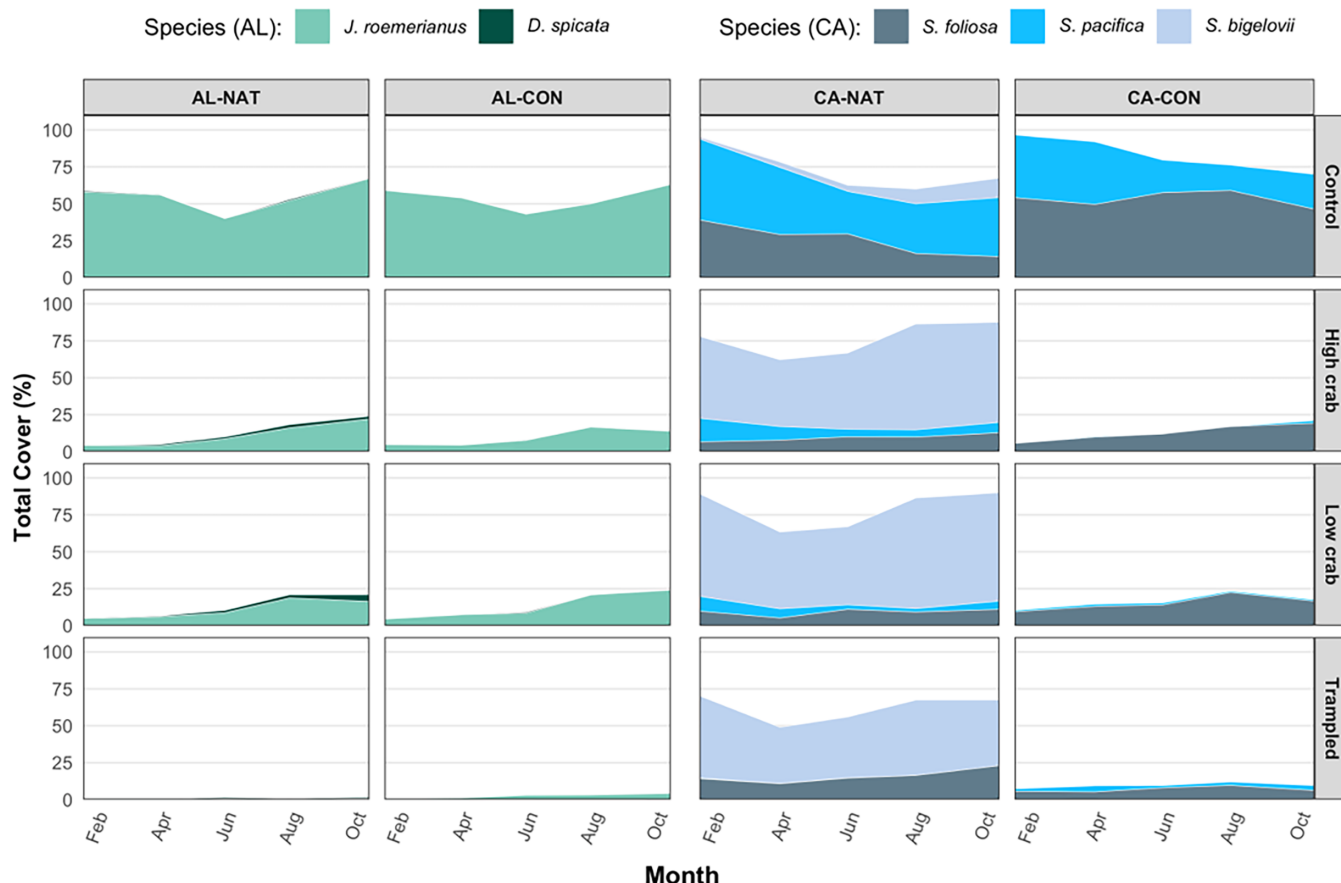
FIGURE 3 The mean total cover (in percentage) of plants in each treatment at each natural (NAT) and constructed (CON) tidal marsh in Alabama (AL) and California (CA) over the growing season (February–October). Each color represents a distinct plant species. For AL-NAT and AL-CON, light green represents the relative percent cover of *Juncus roemerianus* (needlerush) and dark green represents the relative percent cover of *Distichlis spicata*. For CA-NAT and CA-CON, dark blue represents the relative percent cover of *Spartina foliosa* (Pacific cordgrass), aqua represents the relative percent cover of *Sarcocornia pacifica* (pickleweed), and light blue represents the relative percent cover of *Salicornia bigelovii*.

did not impact sediment bulk density at AL-NAT ($p = 0.527$; Appendix S2: Table S2), but they did at AL-CON ($p = 0.005$; Figure 5; Appendix S2: Table S2). Specifically, at AL-CON, sediment bulk density was 68% higher (averaged across all depths) in Trampled plots than in Control plots (Figure 5A). LRRs indicate that researcher effects did not affect bulk density at AL-NAT, but they had negative effects on bulk density at AL-CON (Figure 1).

Depth did not affect SOM at AL-CON ($p = 0.531$; Figure 5B; Appendix S2: Table S2). However, researcher direct and indirect effects decreased SOM at AL-CON by 49%–76% relative to undisturbed Control plots ($p < 0.001$; Figure 5B; Appendix S2: Table S2). At AL-NAT, SOM decreased with depth ($p < 0.001$; Figure 5D; Appendix S2: Table S2). Researcher effects did not impact SOM at AL-NAT ($p = 0.350$; Figure 5D; Appendix S2: Table S2). LRRs indicate there were no researcher effects on SOM at AL-NAT, but there were substantial negative effects of researchers on SOM at AL-CON (Figure 1).

California

Crab populations

Crab burrow density was impacted by Marsh Type ($F = 7.42$, df $= 1$, $p = 0.011$), Treatment ($F = 3.71$, df $= 3$, $p = 0.023$), and their interaction ($F = 2.99$, df $= 3$, $p = 0.048$; Appendix S3: Figure S4). CA-CON had 49% more crab burrows across all treatments than CA-NAT. Treatments had distinct impacts on crab burrow density depending on Marsh Type. Specifically, at CA-CON, there was no effect of Treatment on crab burrow density, while at CA-NAT, Trampled plots had fewer crab burrows than Control, High Crab, and Low Crab plots. These findings were supported by our LRRs, which suggest that researcher impacts had small negative effects on crab burrow density at CA-CON and had variable effects on crab burrow density at CA-NAT. Specifically, trampling decreased burrow density, High Crab manipulations
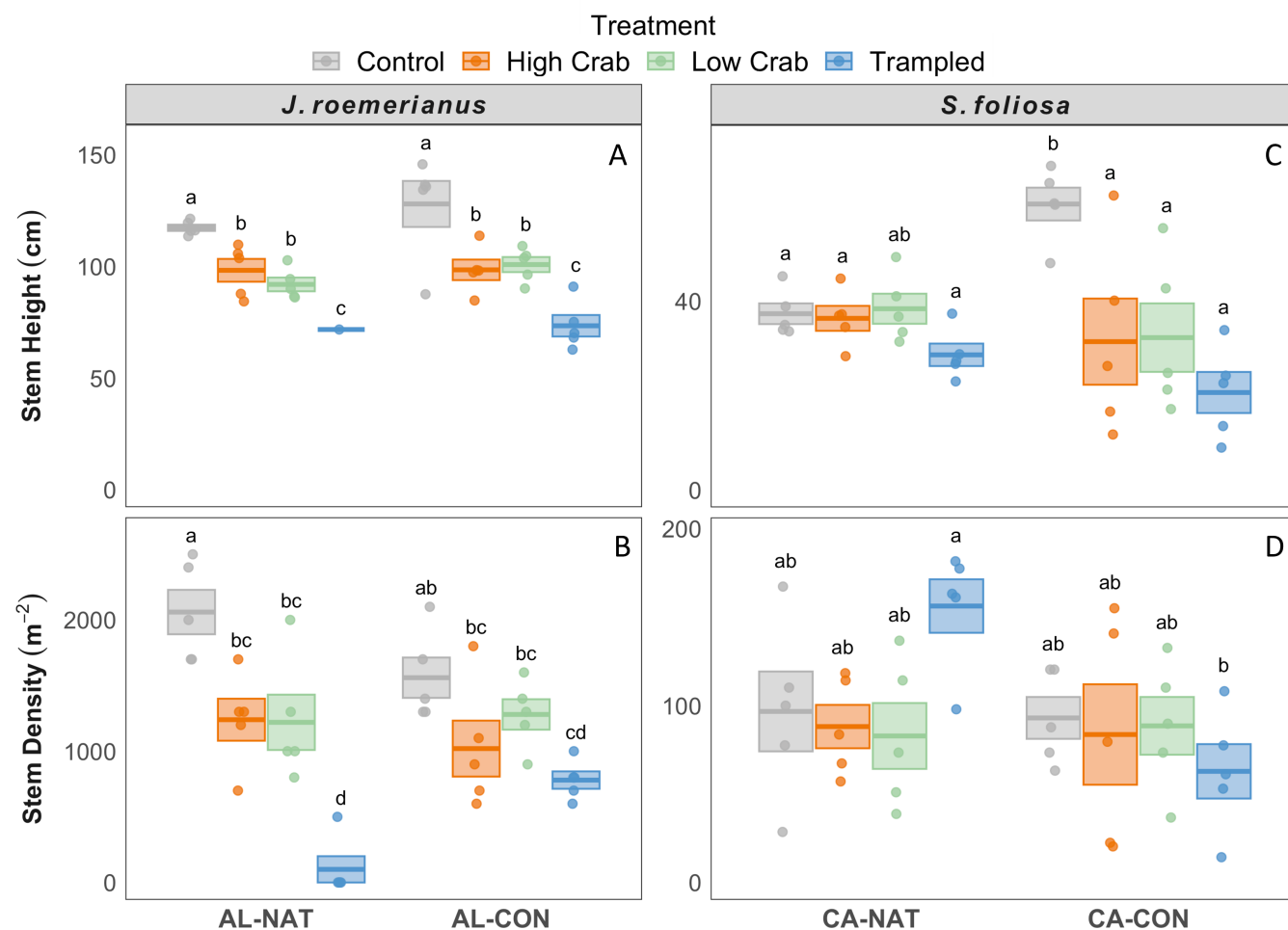
FIGURE 4 (A) Mean stem height and (B) stem density of *Juncus roemerianus* (needlerush) at the end of the growing season in all treatments at the Alabama (AL) natural marsh and constructed marsh (AL-NAT and AL-CON, respectively). (C) Mean stem height and (D) stem density *Spartina foliosa* (Pacific cordgrass) at the end of the growing season in all treatments at the California (CA) natural marsh and constructed marsh (CA-NAT and CA-CON, respectively). Mean stem height is based on the mean of 5 needlerush stems in AL and 10 Pacific cordgrass stems in CA. Lines inside boxes are mean values; box limits represent ±1 SE. Points represent raw data. Letters represent significant interactions between site and treatment (Tukey's honestly significant difference test; $\alpha = 0.05$).

increased burrow density, and Low Crab manipulations had no effect on burrow density (Figure 1).

Plant communities

Marsh Type ($p < 0.001$), Treatment ($p < 0.001$), and their interaction ($p < 0.001$) influenced total plant cover (Figures 1–3; Appendix S2: Table S1; Appendix S3: Figure S2). At CA-NAT, plant cover was similar across all treatments, suggesting that plant cover had recovered to control conditions within one year of researcher impacts (Figures 1–3; Appendix S2: Table S1; Appendix S3: Figure S2). However, High Crab, Low Crab, and Trampled plots at CA-CON had 73%–88% less total plant cover than Control plots after a year of recovery (Figures 2 and 3; Appendix S2: Table S1; Appendix S3: Figure S2). LRRs

suggest that researcher direct and indirect effects had no impact on total plant cover at CA-NAT but decreased total plant cover at CA-CON (Figure 1).

CA-NAT had 29% more Pacific cordgrass stems across all treatments than CA-CON ($p = 0.070$; Figure 4; Appendix S2: Table S1). There was also an interaction between Marsh Type and Treatment on Pacific cordgrass stem density ($p = 0.040$; Appendix S2: Table S1). This interaction was mediated by different effects of trampling on Pacific cordgrass stem density at each marsh. Pacific cordgrass stem density was 32% lower in Trampled plots than in Control plots at CA-CON, while it was 62% higher in Trampled plots than in Control plots at CA-NAT (Figure 4). The opposing effect of researcher trampling on cordgrass stem density between CA-CON and CA-NAT is further supported by our LRRs, which suggest that researcher direct effects had minimal impacts
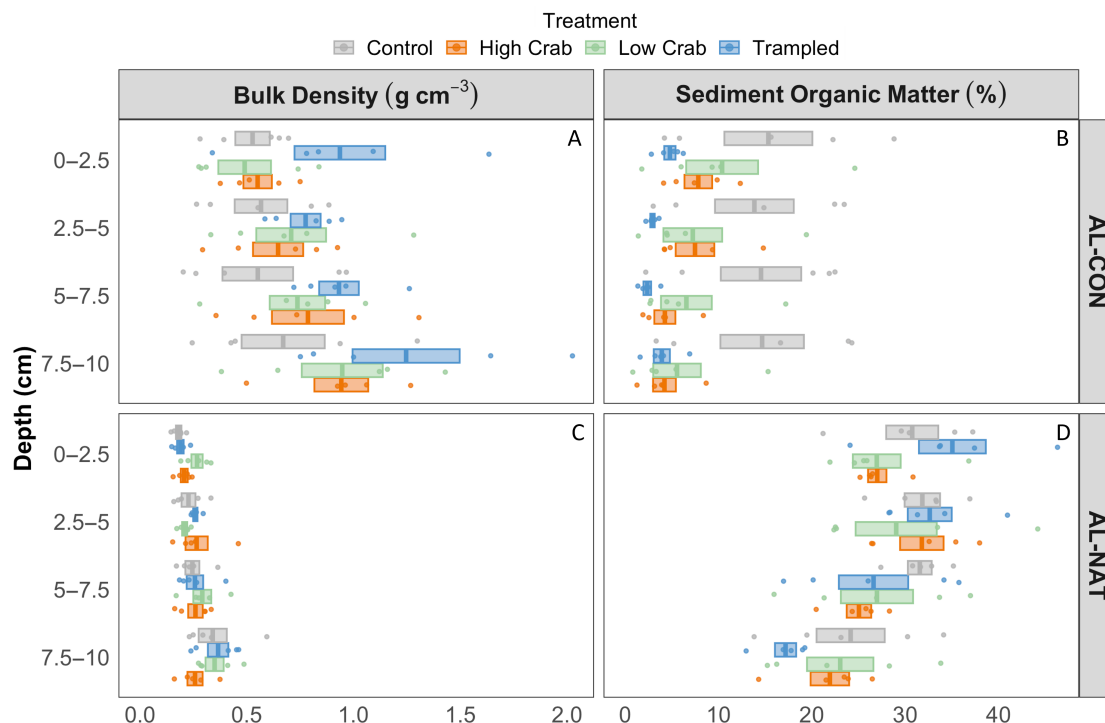
FIGURE 5 (A) Sediment bulk density and (B) sediment organic matter (SOM) by depth in all treatments at the constructed (CON) marsh in Alabama. (C) Sediment bulk density and (D) SOM by depth in all treatments at the natural (NAT) marsh in Alabama. Lines inside boxes are mean values; box limits represent ±1 SE. Points represent raw data.

on Pacific cordgrass stem density at both marshes. However, researcher indirect effects had a slight negative effect on Pacific cordgrass stem density at CA-CON and a slight positive effect on Pacific cordgrass stem density at CA-NAT (Figure 1).

Treatment also affected Pacific cordgrass stem height ($p = 0.001$; Figure 4; Appendix S2: Table S1). There was no effect of Marsh Type or Marsh Type by Treatment interactions on Pacific cordgrass stem height (Appendix S2: Table S1). Pacific cordgrass stems in High Crab, Low Crab, and Trampled plots were 47%–66% shorter than stems in Control plots at CA-CON and were 12%–44% shorter than stems in Control plots at CA-NAT (Figure 4). LRRs suggest that researcher activities had negative effects on Pacific cordgrass stem heights, with these effects being greater at CA-CON than at CA-NAT (Figure 1).

DISCUSSION

We show that researcher direct effects (i.e., sampling and manipulating) and indirect effects (i.e., trampling) have pervasive impacts on crab burrow density, plant cover and traits, and edaphic conditions in Alabama and southern California tidal marshes. In all marsh sites, researcher indirect effects had greater impacts on plant communities and sediment conditions than researcher

direct effects (Figure 1). Additionally, researcher effects (direct and indirect) tended to be greater in Alabama tidal marshes than in southern California tidal marshes, possibly due to differences in the functional traits of dominant plants in the communities of these regions. Researcher impacts were also greater in constructed tidal marshes than in natural tidal marshes across both regions, suggesting that constructed tidal marshes are less resilient to disturbance than natural tidal marshes. Our study highlights the detrimental effects that research-related activities can have on the biological structure and edaphic conditions of field sites and provides unique insights that can help researchers minimize the scientific footprint of their research programs.

Researcher indirect effects associated with trampling had a greater impact on tidal marsh plant community structure and edaphic conditions than researcher direct effects (e.g., manipulated plots; High Crab and Low Crab plots). The profound impacts of researcher trampling on tidal marsh structure are not surprising (despite being rarely documented) for two reasons. First, studies with other large mammals (e.g., reindeer, sheep, cattle) have repeatedly found that mammal trampling has greater impacts on the abundance and composition of plant communities than defoliation from mammal grazing (Lezama & Paruelo, 2016; Narantsetseg et al., 2018; Sørensen et al., 2009). For example, reindeer trampling

in a subarctic grassland decreased the cover of moss (*Pleurozium schreberi*) and sedges (*Carex vaginata*), while reindeer defoliation did not affect plant cover (Sørensen et al., 2009). Thus, the indirect effects of mammals, broadly, on their environments may be greater than their direct effects.

Second, human vegetation trampling associated with recreational activities has well-documented, adverse effects on plant community structure and sediment conditions (Goldman Martone & Wasson, 2008; Pescott & Stewart, 2014). Plant cover in grasslands and forests tends to decline exponentially with increasing human trampling intensity (i.e., number of passes per year; Cole, 1987). In fact, Cole (1987) found that after 200 passes per year, plant cover declined by 31%–95%. We observed faster rates of plant cover loss in our Alabama sites—93%–97% cover loss after approximately 33 passes per year (Trampled relative to Control plots, Figure 3). Thus, studies of recreational human trampling may provide valuable insights, but slightly underestimate researcher trampling effects on plant structure and edaphic conditions at field sites.

While indirect trampling effects were the main pathway by which researchers affected field sites, researcher direct effects did have legacy effects on crab burrow density and belowground plant biomass. For instance, at CA-NAT and AL-NAT, High Crab plots still had 269% and 750%, respectively, more crab burrows than Control plots 10–12 months after the final crab manipulation occurred (Appendix S3: Figures S3 and S4). Crab burrowing can oxygenate and homogenize sediments, which can have indirect effects on plant community composition, organic matter distribution, and decomposition (Bertness, 1985; Bortolus & Iribarne, 1999; Kristensen & Alongi, 2006; Rinehart, Dybiec, Mortazavi, et al., 2023; Walker, Grosholz, & Long, 2021; Walker, Rinehart, et al., 2021). Combined, these results suggest that researcher manipulations of animal populations, such as burrowing crabs, may have long-term cascading effects on the biological structure and ecosystem functions of field sites. While the direct effects of field manipulations are often intentional (e.g., shifting crab burrow densities), the spatial and temporal scales of these impacts should be considered when designing field studies. Specifically, researchers should consider the magnitude of their activities' impacts relative to the (1) size of the field site and (2) vulnerability of the field site to disturbance.

Plant functional traits (e.g., life-form, growth-form) frequently affect the resistance and resilience of plant communities to human disturbance and trampling (Cole, 1987, 1995; Pescott & Stewart, 2014). In fact, plant functional traits are better predictors of trampling effects than the intensity of the trampling, since low-intensity trampling can be as damaging as high-intensity trampling in some plant communities (Pescott & Stewart, 2014). Our study also supports this observation, since natural tidal marshes dominated by Pacific cordgrass had greater resiliency to researcher effects than marshes dominated by needlerush (Figure 1). For instance, after one growing season, Pacific cordgrass stem density was 62% higher in Trampled plots than in Control plots at CA-NAT, while needlerush stem density was still 95% lower in Trampled plots than in Control plots at AL-NAT (Figure 4). Pacific cordgrass is likely more resilient to researcher effects (direct and indirect) than needlerush because it is more stress tolerant and has faster rates of clonal spread (Jones et al., 2016; Touchette et al., 2009). More broadly, marshes dominated by cordgrass species (e.g., *S. foliosa*, *S. alterniflora*, *S. cynosuroides*) and mangroves are likely more resilient to researcher disturbance than marshes dominated by needlerush (Jones et al., 2016; Pennings et al., 2021; Sturchio et al., 2023; Touchette et al., 2009). Thus, it is important that researchers consider the functional traits of the dominant plant communities in their field sites to determine how best to alleviate negative impacts on biological structure.

Researcher direct and indirect effects had stronger, negative effects on plant communities and sediment conditions in our constructed marshes (i.e., AL-CON and CA-CON) than our natural marshes (i.e., AL-NAT and CA-NAT; Figure 1). This difference is likely due to the fact that early-successional ecosystems, including constructed and restored tidal marshes, have less developed ecological memory (i.e., the information [e.g., functional traits, historical disturbance regimes] and material [e.g., seeds/rhizomes, nutrient pools] legacies of an ecosystem that impact its capacity to respond to disturbance) than natural ecosystems (Johnstone et al., 2016). For example, it is well-documented that AL-CON has less belowground plant biomass and smaller nutrient pools than AL-NAT (Ledford et al., 2021; Rinehart, Dybiec, Mortazavi, et al., 2023; Tatariw et al., 2021), suggesting that the ecological memory in AL-CON limits its capacity to recover following disturbance. Similarly, we observed only subordinate species (e.g., *D. spicata* in AL and *S. bigelovii* in CA) colonizing researcher-impacted plots (i.e., High Crab, Low Crab, Trampled) in natural tidal marshes, suggesting that the rhizome/seed banks in the constructed marshes are limited and reduced the capacity of these marshes' plant communities to respond to disturbance.

Ecological memory, like other ecosystem attributes, develops through time; thus, older constructed and restored ecosystems should have greater resistance and resilience to disturbance than younger constructed and restored ecosystems (Johnstone et al., 2016). Our results support

this assumption; researcher effects were less severe in the Alabama constructed marsh, which is twice as old as the California constructed marsh (Figure 1; CA-CON = 17 years, AL-CON = 34; Beheshti et al., 2022, 2023; Vittor et al., 1987). However, even after three decades, AL-CON has not developed the resiliency necessary to recover from researcher direct and indirect effects, which are still evident >2 years after the initial disturbance (Rinehart and Dybiec, personal observation). Consequently, while research on constructed and restored ecosystems is clearly necessary to overcome historical and contemporary rates of ecosystem loss (Aronson et al., 2020; Guan et al., 2019), we advocate that researchers working in these early-successional ecosystems implement strategies to mitigate their scientific footprint (see Figure 6).

Implications for conservation and management

It is well-known that human activities, like trampling, can affect the productivity and overall health of tidal marsh ecosystems and other critical ecosystems worldwide (Bezanson et al., 2013; Cole, 1987, 1995; Goldman Martone & Wasson, 2008; Pescott & Stewart, 2014). However, research activities (e.g., basic research and bioassessment) are vital to understanding, managing, and conserving ecosystems, especially considering the projected impacts of climate change (Odum, 1984). Taking members of the public into these ecosystems on tours also increases support for conservation and decreases hostility between natural reserves and neighboring communities (Davenport et al., 2007). Thus, there is a continued and paradoxical need to disturb critical ecosystems to ensure their longevity and health.

Given this need, field researchers need to act as environmental stewards and work to actively reduce their personal impacts on the ecosystems they study. Past efforts have proposed several strategies for minimizing researcher impacts in specific ecosystems, like wetlands, such as practicing "leave no trace," backfilling soil pits, and using biodegradable materials to mark sampling locations (Bryzek et al., 2022). Based on our study, we support these practices and seek to further promote four key strategies that field researchers can implement to reduce their scientific footprints and limit their impacts on natural and constructed systems (Figure 6).

First, we advocate that researchers work to limit the number of site visits involved in each project. For example, Walker, Grosholz, and Long (2021) and Walker, Rinehart, et al. (2021) monitored crab burrow density and plant communities in their crab manipulation study monthly from approximately April to October in 2016–2018. However, the
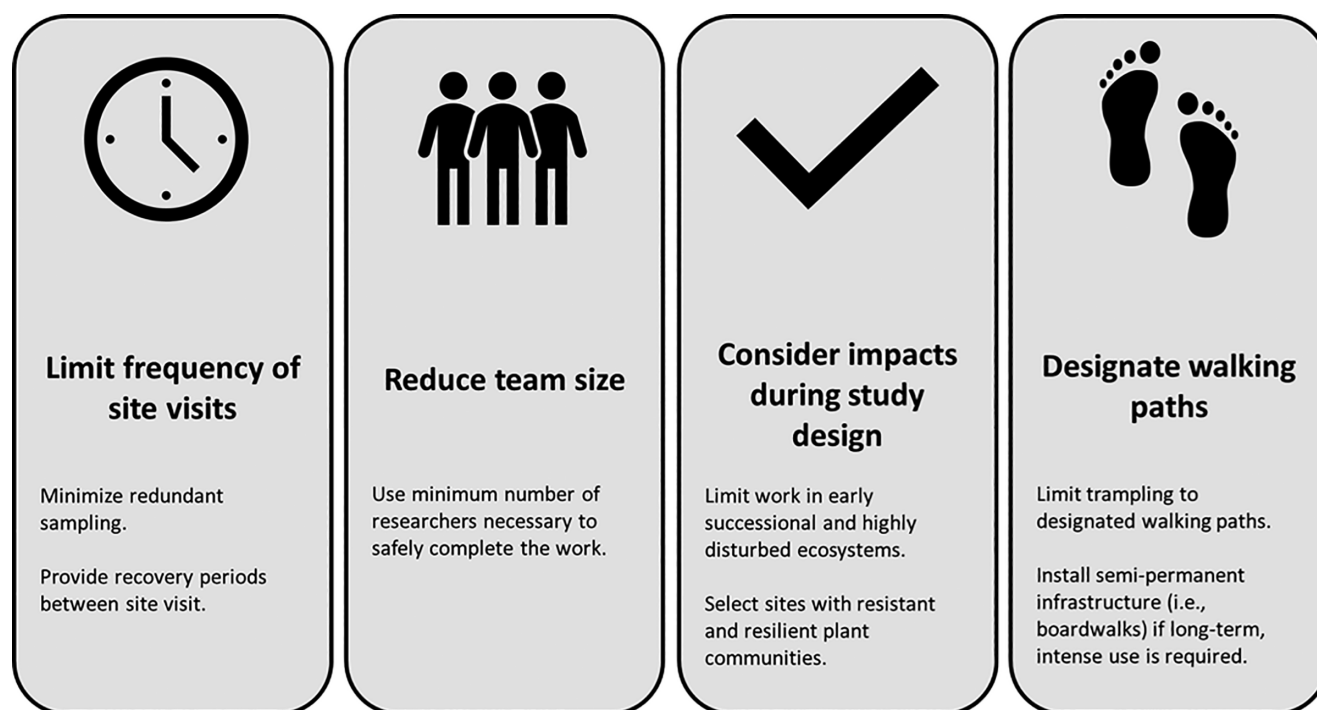
FIGURE 6 Schematic showing the four major strategies that researchers can use to minimize their scientific footprint, including limiting the frequency of site visits, reducing team size, considering impacts during experimental design, and designating researcher walking trails.

main data used in the final manuscripts were from the final sampling time point (October) of each year. Thus, these same data could have been collected with at least 21 fewer site visits (42–84 fewer trail passes), which would have reduced the scientific footprint of these field studies considerably. Similarly, in our current studies, we could have further reduced our site visitations and still produced a scientifically rigorous and informative dataset. This modification would have further limited our trampling effects on plant communities, especially early in the growing season when plants are smaller and likely more vulnerable. Reducing visitations may be easier for researchers with long histories working at specific sites, since they have a more nuanced understanding of site phenology.

Second, we advocate that researchers limit the size of their field teams to the minimum number of researchers needed to safely complete the research. Reducing the number of researchers in the field will limit the amount of trampling activity and further reduce other indirect researcher effects, like trash and litter (see Bryzek et al., 2022), not assessed in our current study. Overall, researchers should work to optimize the frequency (visits) and intensity (team size) of their field activities to inflict the least amount of disturbance possible.

Third, we strongly encourage researchers to think about the environmental impacts of their studies during the design phase. This approach will provide the ideal opportunity to reflect on which sampling time points and variables are essential, which sampling time points and variables could be eliminated, and how many researchers will be needed to complete each task in the field. Additionally, by considering environmental impacts during the design phase, researchers can think about which field sites may be the most resilient to their activities and minimize their use of sensitive ecosystems, like restored and constructed habitats, whenever possible. For instance, we may consider limiting our use of these sensitive ecosystems to only research activities that are vital to the management and conservation of the site (e.g., monitoring) and the species that inhabit it (e.g., threatened and endangered species).

Fourth, given that even low-intensity trampling can damage some plant communities (Pescott & Stewart, 2014), researchers should try to designate walking paths to minimize the area being disturbed by trampling (Bryzek et al., 2022). While using a single path will have dramatic negative effects on the habitat along that path, localizing those impacts to a single path, rather than multiple paths, should limit the overall impact that research teams have on their field sites. Additionally, in highly sensitive ecosystems, it may be valuable to install semipermanent infrastructure, like boardwalks, if the research will require >200 passes of a single path, since several plant communities are reduced to <90% total cover after this level of disturbance (Cole, 1987). Other semipermanent infrastructure like flume weirs, bottomless lift nets, and marsh organs can also be implemented to minimize researcher disturbance to marsh habitats (Kneib, 1991; Morris et al., 2013; Rozas, 1992). However, installing such infrastructure is expensive, time intensive, and may not be possible (or permissible) at all field sites—which is what kept our team from using boardwalks during our field studies. Granting agencies should encourage researchers to include mitigation expenses (e.g., boardwalk installation) in their proposals and provide funding to support such actions when permissible.

Our research revealed direct and indirect researcher effects to natural and constructed tidal marsh ecosystems that altered biological structure and sediment conditions for at least a year post-impact. These sorts of research impacts are likely common in other habitat types and may be more severe in early-successional or restored ecosystems. However, these types of field studies are essential to understand ecological processes. Thus, our intention in this study is not to reduce the amount of field research occurring or diminish the importance of field research; rather, we seek to encourage our community of field researchers to (1) think more critically about the environmental impacts of their research and (2) start implementing simple strategies (see Figure 6) that will help reduce our collective scientific footprint.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Rinehart, Dybiec, Richardson, et al., 2023) are available from Dryad: https://doi.org/10.25338/B84H18.

ORCID

Shelby A. Rinehart 🅲 https://orcid.org/0000-0001-9820-1350

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.