Ambio 2022, 51:2524–2531
https://doi.org/10.1007/s13280-022-01756-6

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Check for updates

PERSPECTIVE

Ecological integrity and conservation challenges in a rapidly changing Arctic: A call for new approaches in large intact landscapes

E. Jamie Trammell, Matthew L. Carlson, Joel H. Reynolds, Jason J. Taylor, Niels M. Schmidt

Received: 16 December 2021 / Revised: 15 May 2022 / Accepted: 8 June 2022 / Published online: 2 July 2022

Abstract Intactness is a commonly used measure of ecological integrity, especially when evaluating conservation status at the landscape scale. We argue that in the large and relatively unfragmented landscapes of the Arctic and sub-Arctic, intactness provides only partial insight for managers charged with maintaining ecological integrity. A recent landscape assessment suggests that 95% of Alaska shows no measured direct or indirect impacts of human development on the landscape. However, the current exceptionally high levels of intactness in Alaska, and throughout the Arctic and sub-Arctic, do not adequately reflect impacts to the region's ecological integrity caused by indirect stressors, such as a rapidly changing climate and the subsequent loss of the cryosphere. Thus, it can be difficult to measure, and manage, some of the conservation challenges presented by the ecological context of these systems. The dominant drivers of change, and their associated ecological and socioeconomic impacts, vary as systems decline in ecological integrity from very high to high, and to intermediate levels, but this is not well understood in the literature. Arctic and sub-Arctic systems, as well as other large intact areas, provide unique opportunities for conservation planning, but require tools and approaches appropriate to unfragmented landscapes undergoing rapid climate-driven ecological transformation. We conclude with possible directions for developing more appropriate metrics for measuring ecological integrity in these systems.

Keywords Alaska · Intactness · Landscape approach · Management

INTRODUCTION

> The wealth of biological detail on the tundra dispels any feeling that the land is empty; and its likeness to a stage suggests impending events… It is hard to travel in the Arctic today and not be struck by the evidence of recent change…
> -Barry Lopez, *Arctic Dreams*

Conservation biology as a scientific field emerged, in part, in response to recognizing the value of diverse natural resources and acute resource management needs in the face of increasing threats (Gibbons 1992; Meffe et al. 2006). As conservation biologists identify drivers of ecosystem change, such as habitat fragmentation or climate change, they develop new analytical frameworks and tools to inform proactive (Beyer et al. 2020) and precautionary management strategies (Redford and Sanjayan 2003). Ecological and landscape integrity assessments (EIAs) are one such framework used to inform conservation management. However, ecological integrity is an abstraction, and not an observable or measurable entity in its own right. It is a translation of Leopold's (1949) well-known statement: "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise….." Recent critiques highlight the difficulty in defining ecological integrity (Rohwer and Marris 2021) beyond the commonly used, but imprecise, definition of Parrish et al. (2003) as "the ability of an ecological system to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region." Despite the lack of clarity, ecological integrity remains a core value embedded within resource management organizations, including within agency policy (for example, see NPS 2006). Thus, measuring and subsequently protecting ecological integrity is a core conservation goal for many agencies and organizations.

The most common approach for estimating ecological integrity is through mapping ecological or landscape intactness. Intactness, defined by Carter et al. (2017), is a "quantifiable estimate[s] of naturalness measured on a gradient of anthropogenic influence across broad landscapes or ecoregions." Based primarily on geospatial human footprint data, intactness is a readily available, and therefore heavily utilized, proxy for ecological integrity (McGarigal et al. 2018). The assessments based on spatial data of human activities and infrastructure (i.e., human footprint Venter et al. 2016) are often expanded to include areas of influence associated with each specific activity to estimate where and how habitats are impacted and fragmented, creating a continuous estimate of intactness (Theobald 2013; Brown and Williams 2016; Wurtzebach and Schultz 2016; Hak and Comer 2017; Walston and Hartmann 2018).

In anthropogenically dominated landscapes, as in much of the contiguous US, Europe, and eastern Asia, the dominant drivers of change and greatest influence on ecological integrity have been habitat loss and landscape fragmentation (see Millennium Ecosystem Assessment 2005; Rybicki and Hanski 2013). Natural habitats within those regions are considered those that have not been fragmented by habitat loss. Appropriately, conservation biologists and planners working in fragmented systems have typically evaluated landscape pattern or spatial characteristics (see Taylor et al. 2007, 2016) based on the patch–corridor–matrix model of landscape ecology as a basis of assessing connectivity (Turner et al. 2001). In turn, habitat availability and connectivity have been the focal attributes for understanding an ecosystem's conservation status and thus, integrity of ecological function (BLM 2012; Tallis et al. 2015; McGarigal et al. 2018).

However, in the relatively unfragmented landscapes of the Arctic and sub-Arctic, mapping intactness (or connectivity) is less informative for management agencies needing to protect ecological integrity. In recent calculations of intactness performed for the state of Alaska, Trammell and Aisu (2015) and Reynolds et al. (2018) found that over 95% of the state of Alaska has "very high" intactness. We explore this example in order to better understand the utility of such an estimate, and challenge the use of this common ecological integrity measure in non-anthropogenically dominated landscapes.

LANDSCAPE INTACTNESS IN ALASKA

Utilizing the Landscape Condition Model (Hak and Comer 2017), a common landscape approach tool used throughout the western US, Trammell and Aisu (2015) mapped the impacted areas in Alaska associated with direct land conversion or use (such as highways, ice roads, logging), and areas associated with indirect impacts (such as invasive species infestations; Fig. 1). Their assessment found that approximately 95% of the state has "very high" intactness (defined as very little to no human modification), and 3% of the state has "high" or "medium" intactness, while less than 0.5% has "very low" intactness. Very few areas in the contiguous US approach these levels of intactness, including those areas that have been intensely managed for biodiversity and protected from development for over a century (Trammell and Aisu 2015). Yet, when summed across all levels of impact, approximately 86 000 km^2 of Alaska is directly or indirectly modified by human development (Trammell and Aisu 2015), approximately the area of Ireland. While fragmentation effects may appear relatively small in terms of percentage of area, the absolute area of habitat lost or impacted, such as wetlands filled, placer mines constructed, or forests clear-cut, is far from negligible. Furthermore, levels of intactness do not appear to be related to levels of biodiversity protection (Reynolds et al. 2018). Alaska's size and relatively high levels of intactness, as traditionally measured, lead to a common (mis)perception that it can absorb significant landscape change without loss of ecosystem services and ecological integrity.

IMPLICATIONS OF MANAGING FOR INTACTNESS

With intactness-based estimates for ecological integrity, it can be difficult to recognize the emerging conservation challenges in the socio-ecological systems of the Arctic and sub-Arctic. For example, existing development has already generated detectable impacts on a variety of important subsistence species. These impacts include reduced gene flow in moose (*Alces alces*) populations along fenced highway corridors (Wilson et al. 2015) and changes in caribou (*Rangifer tarandus*) habitat-use (Joly et al. 2006) and migratory behaviors (Wilson et al. 2016) in relation to industrial roads. Management actions are typically only activated when species are at risk of extinction (i.e., when there is a "crisis"), not when among-population gene flow is reduced by a small percent or behaviors and migratory routes are altered due to human infrastructure. However, ecological phenomena such as large-scale mammal migrations have been lost in most regions of the

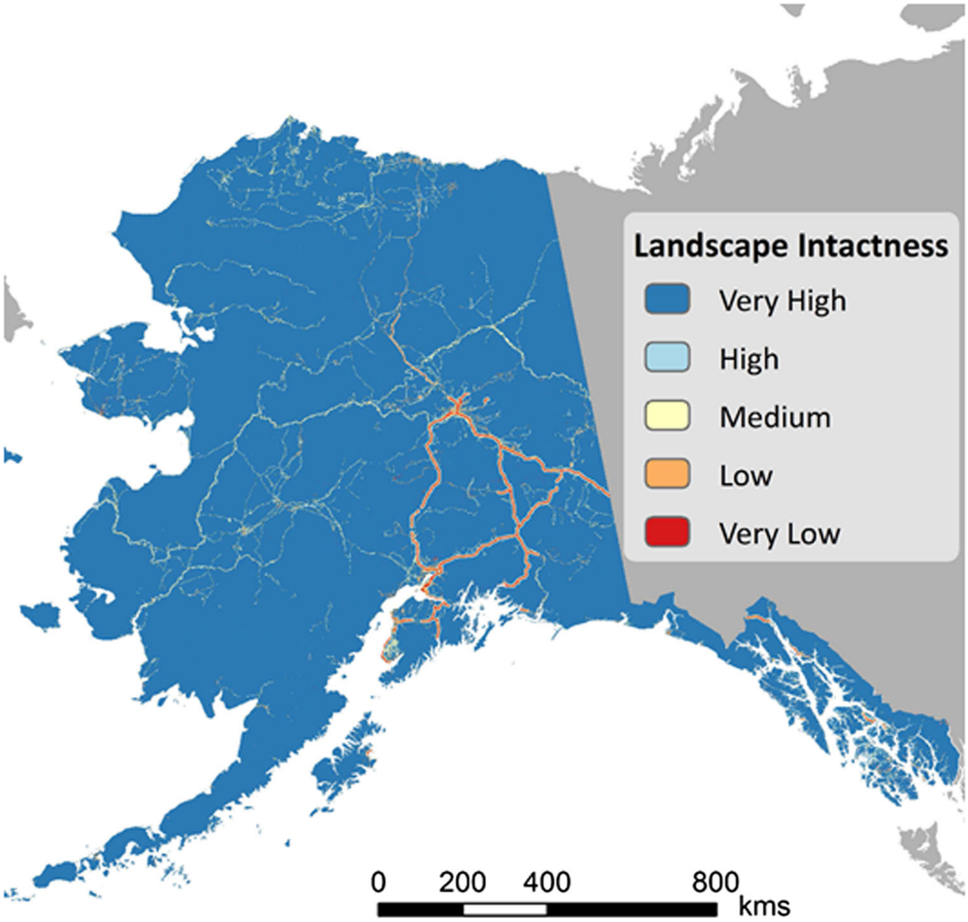

Fig. 1 Landscape intactness, as modeled by the landscape condition model for Alaska (modified from Reynolds et al. 2018). Categories represent relative intactness according to the Landscape Condition Model score. The Aleutian Archipelago is omitted to provide adequate viewable resolution of the rest of the state

world and therefore represent an increasingly important ecological process to conserve (Joly et al. 2019).

Additionally, the adoption of intactness metrics developed for use in other less pristine environments leads to a lack of resolution in conservation assessments in largely intact regions. For example, the NatureServe Network Conservation Rank Calculator (Faber-Langendoen et al. 2009) is used to provide conservation ranks for species throughout the Western Hemisphere. However, that tool was designed for very different ecological conditions than exist in the Arctic and sub-Arctic. This calculator heavily weights area of occupancy and percentage of occurrences in areas of "good ecological integrity." The scoring for ecological integrity in this tool asymptotes to a maximum value when just 40% or more of the total area occupied by a species has 'good or excellent ecological integrity,' providing very little resolution for species in highly intact systems. In the case of Alaska, the high intactness estimate causes a false sense of low conservation need (see Flagstad et al. 2019). This can be particularly problematic in the Arctic where ecological systems are very dynamic (e.g., Schmidt et al. 2016) and single weather events can cause catastrophic die-offs of populations over very broad geographies (Tyler 2010; Hansen et al. 2014) or even community-wide failures of reproduction (Schmidt et al. 2019).

Spatial variability and unique and unpredictable responses are emerging as dominant patterns of change in Arctic and sub-Arctic ecosystems (Taylor et al. 2020). Major drivers of change include the climate that is warming at a rate more than twice the global average (Hinzman et al. 2005; Osborne et al. 2018), which has triggered large-scale herbivorous insect outbreaks and increases in size, frequency, and severity of fires, leading to a dieback of North American boreal forests and a potential ecosystem shift from a carbon sink to a carbon source (Walker et al. 2019). Across the low Arctic and sub-Arctic, permafrost is irreversibly thawing, releasing large stores of greenhouse gases (Lenton et al. 2019) and draining thousands of hectares of wetlands (Avis et al. 2011). In recent decades, the Eurasian Arctic and sub-Arctic have been dramatically transformed from land use changes resulting from large-scale fires, losses of lakes, and pollution, and deforestation, changes that threaten the region's natural ecosystems, particularly when coupled with the ecological transformations driven by persistent directional climate change (Groisman et al. 2017).

The large-scale climate and cryosphere changes observed in Alaska suggest major ecological transformations are already underway (Markon et al. 2018). The ecological integrity of these systems is strongly tied to the extreme seasonal variation in climate, particularly in regard to low temperatures and short growing seasons (see Arctic Biodiversity Assessment 2013). The Arctic and sub-Arctic uniqueness is reflected in climate regimes that (1) are largely responsible for specific structural attributes of these ecosystems, such as sea-ice, permafrost, frost-boils, beaded streams, pingos, and persistent snow cover; (2) drive strong seasonality in trophic relationships and life histories (Schmidt et al. 2017); and (3) select for specialized physiological and morphological traits in diverse organisms (Billings 1974; Danks 2004; Lin et al. 2019). Yet the Arctic is warming at a dramatic pace (Hinzman et al. 2005; Osborne et al. 2018; Box et al. 2019), with an estimated reduction of at least 20 fewer nights below freezing by mid-century, and more than 45 less nights below freezing in the Arctic and sub-Arctic coastal regions of Alaska, under the "business as usual" RCP8.5 emission scenario (Markon et al. 2018). These changes, and the other direct impacts of climate change on the hydrological cycle (Littell et al. 2018) and growing season length (Bieniek et al. 2015; Arndt et al. 2019), suggest major ecological alternations are imminent (see National Resource Council 2014).

Other known or expected drivers of ecological change in the Arctic and sub-Arctic that should be accounted for in an indicator for ecological integrity includes (1) transport and deposition of persistent pollutants into the region, as well as local point source pollutants, which adversely affect both ecosystem and human health (Law and Stohl 2007; AMAP 2018); (2) invasive species, as increasing examples of establishment and spread have been noted and are expected to be exacerbated by climate change (Sanderson et al. 2012; Lassuy and Lewis 2013; Chan et al. 2019; Wasowicz et al. 2020); and 3) the legacy effects of earlier industrial-scale overharvesting of wildlife populations (Arctic Biodiversity Assessment 2013). These drivers of change (climate, cryosphere, persistent pollutants, invasive species vulnerability, and wildlife overharvest) are rarely accounted for in intactness estimates or other ecological integrity metrics focused strictly on characteristics of the composition and spatial distribution of unfragmented areas (McGarigal et al. 2018), undermining the effectiveness of such metrics in evaluating tradeoffs among competing management decisions.

GLOBAL SIGNIFICANCE AND ALTERNATIVE APPROACHES

Large intact areas are not unique to the Arctic and sub-Arctic. Large Wild Areas (LWAs), defined by having a low human footprint and low levels of intensive land use (Locke et al. 2019), share some common features, such as providing a range of ecological services of local, regional, and global importance (e.g., subsistence resources, clean water, carbon sequestration; Huntington et al. 2013; USGCRP 2018) and strong direct reliance of local cultures on the region's ecosystem services and processes (Chapin et al. 2004; Huntington et al. 2013). Additionally, LWAs often support relatively unimpeded seasonal migration and wide-ranging behaviors of many terrestrial (such as caribou), aquatic (such as salmon), and avian species (such as white-fronted geese). In LWAs, developed regions may be better described by the 'conservation matrix' landscape model (Schmiegelow et al. 2014), where the human footprint occurs in patches within a background matrix of relatively intact landscapes, rather than the patch–corridor model of fragmented and modified landscapes. The high level of intactness, as traditionally measured, in an LWA can often be an historical function of low human population and logistical constraints, rather than being the product of policy or management, and can be misleading (as described above). Thus, many LWAs are susceptible to potential unregulated habitat conversion if not accurately assessed and managed for conservation threats (Beyer et al. 2020), threats that may be missed if evaluated using common intactness measures.

Based on the points raised here, we suspect that regional or global assessments of LWAs that use traditionally measured intactness are inadequate and provide an overestimate of the true integrity of these systems. Alternative approaches that reflect the nature of the stressors, natural resources of interest, and landscape context are warranted. Belote et al. (2019) argue for 'condition-specific targets' as part of the landscape approach to conservation, but they still largely focus on limiting fragmentation. We suggest a more effective approach would be to combine condition-specific targets with a modification of an index of ecological integrity similar to that developed by McGarigal et al. (2018). However, in this case, metrics related to important components driving short-term and long-term system resiliency would need to be included like ecological rates of change and amplifying and dampening mechanisms, highlighted by Crausbay et al. (2022) in the context of managing for ecological transformation.

Additionally, biotic responses to environmental change, and thus the ecological outcome of a perturbation (e.g., Schmidt et al. 2017), generally takes place at a much smaller scale than is traditionally mapped in intactness estimates. Local-scale processes need to be captured in broad-scale measures to accurately model ecological integrity. On-going monitoring initiatives, for example the Circumpolar Biodiversity Monitoring Program (CBMP; https://www.caff.is/monitoring; Christensen et al. 2013) is working collaboratively with other global programs to assemble data about locally important biodiversity components and their likely drivers of change. Such monitoring programs allow access to pan-Arctic data and analytical results that can be tied to drivers (anthropogenic or non-anthropogenic) when modeling ecological integrity across broad geographies, thereby providing a crucial link between local and landscape-scale processes.

Arctic and sub-Arctic systems need a measure of ecological integrity that can account for the projected changes in system dynamics, as well as the accompanying uncertainties. This suggests a very different, information-heavy approach will be required to incorporate not only core features of structure, composition, and function (Walston and Hartmann 2018), but also their projected trajectories in response to environmental changes. It would remain an open question how to apply such an index over planning time scales that could include climate-driven system transformations, which appear to exceed the limits of resiliency. While promising, this approach would require substantially more data and understanding (Crausbay et al. 2022; Lynch et al. 2022), at much finer scales (Schmidt et al. 2017) than currently exists for many LWAs, especially those in the Arctic and sub-Arctic (see Trammell et al. 2016).

CONCLUSION

To be effective for conservation in the Arctic and sub-Arctic, an indicator of ecological integrity must include the characteristics identified in Box 1.

Box 1 Effective indicators of ecological integrity in the Arctic and sub-Arctic should include:

- Ecological condition-specific targets
- Incorporation of ecologically relevant data to address short-term and long-term responses of the system, at a minimum would include:
  - Permanent and seasonal anthropogenic footprint
  - Climate-linked perturbation
  - Direct and indirect pollution
  - Invasive species
  - Legacy or contemporary overharvesting
- Linkage of local-scale processes to landscape-scale models

Foremost, the measure has to account for major drivers of change beyond just land use (McGarigal et al. 2018) and at biological relevant scales, not just the scales at which landscape-level data currently exists. Additionally, significant progress is needed to better understand the relationship between ecological integrity and chosen indicators to translate projected changes in the indicator's value into meaningful conservation information. For example, if intactness is used as the indicator, what important ecological functions are likely to be impacted or lost when intactness declines from 100 to 95%? On the surface, 5% reduction in intactness seems irrelevant, but we know this to be untrue, especially if it is estimated over ecoregions that are more than 5 million ha in size, as is the case in Alaska. As we have described above, LWAs like the Arctic and sub-Arctic are undergoing major observable changes and/or are on the verge of crossing significant ecological thresholds. If considering intactness as a conservation indicator in an LWA, the important questions are; what other threats to ecological integrity that may be difficult to measure are omitted, and how are they likely to influence integrity of a given system? This will require substantially more integrative scenario-based modeling that fully explores the variability around climate and human development projections and accounts for plausible ecosystem transformation (Schuurman et al. 2021; Crausbay et al. 2022). Additionally, there needs to be a clear understanding of (or agreement to), the reference or desired ecological condition so appropriate thresholds can be identified, allowing resource managers to determine if they need to resist, accept, or direct the ecological changes (Lynch et al. 2022). Finally, data must be systematically collected in these other domains using programs like the CBMP or "Ecosystem Classification" approach by McLennan et al. (2018) that uses vegetation as an integrator of productivity, structure, and composition shaped by long-term abiotic drivers and ecological processes, so that LWAs can have metrics that can be relatively quickly and reliably calculated.

Alaska, the broader circum-Arctic, and other regions with LWAs represent some of the few remaining places on the planet where ecological processes have not been directly altered by an ever-expanding modern human footprint (Chapin et al. 2006). These landscapes, in which it is impossible to not be struck by recent changes, as Lopez reminds us in *Arctic*

Dreams, provide an unparalleled global opportunity to make wise management choices aligned with broader system dynamics to better preserve these special places. Then all levels of biodiversity, as well as local communities, will be able to continue accessing the ecosystem services they so critically rely upon. Successful conservation in a rapidly changing Arctic will only be achieved with establishment of more ecoregionally tuned conservation thinking and tools appropriate for these intact and LWAs.

Acknowledgements The US Bureau of Land Management, US National Park Service, and the Alaska Center for Conservation Science at University of Alaska Anchorage supported this study. Monica L. McTeague, Megumi Aisu, Priscilla Lema, and Marcus Geist provided conceptual and analytical GIS support, and figure preparation. Sincere thanks to the all the staff of the Landscape Conservation Cooperatives, both in Alaska and across the US and its territories, for invigorating discussions on these topics—especially Karen Murphy, Philip Martin, Aaron Poe, Amanda Sesser, and Greg Balogh. Additionally, we thank Karen Kelleher and Travis Haby with the BLM for initial conversations around how to apply the landscape approach in Alaska. Finally, we appreciate the insightful and appropriately challenging comments from anonymous reviewers.

REFERENCES

AMAP. 2018. *AMAP Assessment 2018: Biological effects of contaminants on Arctic wildlife and fish*. Tromsø: Arctic Monitoring and Assessment Programme (AMAP). amap.no/documents/download/3080/inline.

Arctic Biodiversity Assessment. 2013. In *Arctic biodiversity synthesis*, ed. H. Meltofte. Akureyri: Conservation of Arctic Flora and Fauna (CAFF), Arctic Biodiversity Assessment.

Arndt, K.A., M.J. Santos, S. Ustin, S.J. Davidson, D. Stow, W.C. Oechel, T.T. Tran, B. Graybill, et al. 2019. Arctic greening associated with lengthening growing seasons in Northern Alaska. *Environmental Research Letters* 14: 125018. https://doi.org/10.1088/1748-9326/ab5e26.

Avis, C.A., A.J. Weaver, and K.J. Meissner. 2011. Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geoscience* 4: 444–448.

Belote, R.T., P. Beier, T. Creech, Z. Wurtzebach, and G. Tabor. 2019. A framework for developing connectivity targets and indicators to guide global conservation efforts. *BioScience* 70: 122–125. https://doi.org/10.1093/biosci/biz148.

Beyer, H.L., O. Venter, H.S. Grantham, and J.E.M. Watson. 2020. Substantial losses in ecoregion intactness highlights urgency of globally coordinated action. *Conservation Letters* 13: e12692. https://doi.org/10.1111/conl.12692.

Bieniek, P.A., U.S. Bhatt, D.A. Walker, M.K. Raynolds, J.C. Comiso, H.E. Epstein, J.E. Pinzon, C.J. Tucker, et al. 2015. Climate drivers linked to changing seasonality of Alaska coastal tundra vegetation productivity. *Earth Interactions* 19: 1–29.

Billings, W.D. 1974. Adaptations and origins of alpine plants. *Arctic and Alpine Research* 6: 129–142. https://doi.org/10.1080/00040851.1974.12003769.

BLM (Bureau of Land Management). 2012. *The Bureau of Land Managements landscape approach for managing the public lands*. IB 2012-058. https://www.blm.gov/policy/ib-2012-058. Accessed 17 June 2021.

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-J.W. Parmentier, R. Brown, U.S. Bhatt, et al. 2019. Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters* 14: 045010.

Brown, E.D., and B.K. Williams. 2016. Ecological integrity assessment as a metric of biodiversity: Are we measuring what we say we are? *Biodiversity Conservation* 25: 1011–1035.

Carter, S.K., N.B. Carr, K.H. Miller, and D.J.A. Wood. 2017. *Multiscale guidance and tools for implementing a landscape approach to resource management in the Bureau of Land Management*. U.S. Geological Survey Open-File Report 2016–1207. https://doi.org/10.3133/ofr20161207.

Chan, F.T., K. Stanislawczyk, A.C. Sneekes, A. Dvoretsky, S. Gollasch, D. Minchin, M. David, A. Jelmert, et al. 2019. Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Global Change Biology* 25: 25–38. https://doi.org/10.1111/gcb.14469.

Chapin, F.S., III., G. Peterson, F. Berkes, T.V. Callaghan, P. Angelstam, M. Apps, C. Beier, Y. Bergeron, et al. 2004. Resilience and vulnerability of northern regions to social and environmental change. *Ambio* 33: 344–349. https://doi.org/10.1639/0044-7447(2004)033[0344:RAVONR]2.0.CO;2.

Chapin, F.S., III., M. Hoel, S.R. Carpenter, J. Lubchenco, B. Walker, T.V. Callaghan, C. Folke, S.A. Levin, et al. 2006. Building resilience and adaptation to manage Arctic change. *Ambio* 35: 198–202. https://doi.org/10.1579/0044-7447(2006)35[198:BRAATM]2.0.CO;2.

Christensen, T., J. Payne, M. Doyle, G. Ibarguchi, J. Taylor, N.M. Schmidt, M. Gill, M. Svoboda, et al. 2013. *The Arctic Terrestrial Biodiversity Monitoring Plan. CAFF Monitoring Series Report Nr. 7*. CAFF International Secretariat. Akureyri, Iceland. ISBN 978-9935-431-26-4. http://hdl.handle.net/11374/230. Accessed 17 June 2021.

Crausbay, S.D., H.R. Sofaer, A.W. Cravens, B.C. Chaffin, K.R. Clifford, J.E. Gross, C.N. Knapp, D.J. Lawrence, et al. 2022. A science agenda to inform natural resource management decisions in an era of ecological transformation. *BioScience* 72: 71–90. https://doi.org/10.1093/biosci/biab102.

Danks, H.V. 2004. Seasonal adaptations in Arctic insects. *Integrative and Comparative Biology* 44: 85–94. https://doi.org/10.1093/icb/44.2.85.

Faber-Langendoen, D., L. Master, A. Tomaino, K. Snow, R. Bittman, G. Hammerson, B. Heidel, J. Nichols, et al. 2009. *NatureServe conservation status ranking system: Methodology for rank assignment*. Arlington: NatureServe.

Flagstad, L.A., K.W. Boggs, T.V. Boucher, M.L. Carlson, M.A. Steer, B. Bernard, M. Aisu, P. Lema, et al. 2019. Assessing the gap between conservation need and protection status for select rare ecosystems in Alaska. *Conservation Science and Practice*. https://doi.org/10.1111/csp2.47.

Gibbons, A. 1992. Conservation Biology in the Fast Lane: Funding for this new kind of study has zoomed up—Along with the number of academic programs—But critics think it's more a fad than a new scientific discipline. *Science* 255: 20–22. https://doi.org/10.1126/science.255.5040.20.

Groisman, P., H. Shugart, D. Kicklighter, G. Henebry, N. Tchebakova, S. Maksyutov, E. Monier, G. Gutman, et al. 2017. Northern Eurasia Future Initiative (NEFI): Facing the challenges and pathways of global change in the twenty-first century. *Progress in Earth and Planetary Science* 4: 41. https://doi.org/10.1186/s40645-017-0154-5.

Hak, J.C., and P.J. Comer. 2017. Modeling landscape condition for biodiversity assessment—Application in temperate North America. *Ecological Indicators* 82: 206–216.

Hansen, B.B., K. Isaksen, R.E. Benestad, J. Kohler, Å.Ø. Pedersen, L.E. Loe, S.J. Coulson, J.O. Larsen, et al. 2014. Warmer and wetter winters: Characteristics and implication of an extreme weather event in the High Arctic. *Environmental Research Letters* 9: 114021. https://doi.org/10.1088/1748-9326/9/11/114021.

Hinzman, L.D., N.D. Bettez, W. Robert Bolton, F. Stuart Chapin, M.B. Dyurgerov, C.L. Fastie, B. Griffith, R.D. Hollister, et al. 2005. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change* 72: 251–298. https://doi.org/10.1007/s10584-005-5352-2.

Huntington, H.P., O. Anisimova, T. Christensen, T. Fenge, A.H. Hoel, T. Jung, K. Klokov, F. Merkel, et al. 2013. *Provisioning and cultural services*, 592–626 in Arctic Biodiversity Assessment, Conservation of Arctic Flora and Fauna, Arctic Council. www.arcticbiodiversity.is.

Joly, K., C. Nellemann, and I. Vistnes. 2006. A reevaluation of caribou distribution near an oilfield road on Alaska's North Slope. *Wildlife Society Bulletin* 34: 866–869.

Joly, K., E. Gurarie, M.S. Sorum, P. Kaczensky, M.D. Cameron, A.F. Jakes, B.L. Borg, D. Nandintsetseg, et al. 2019. Longest terrestrial migrations and movements around the world. *Science Reports* 9: 15333. https://doi.org/10.1038/s41598-019-51884-5.

Lassuy, D.R., and P.N. Lewis. 2013. Invasive species: Human-induced. In *Arctic biodiversity assessment. Status and trends in Arctic biodiversity*, ed. H. Meltofte, A.B. Josefson, and D. Payer, 558–565. Akureyri: CAFF. http://arcticlcc.org/assets/resources/ABA2013Science.pdf. Accessed 17 June 2021.

Law, K.S., and A. Stohl. 2007. Arctic air pollution: Origins and impacts. *Science* 315: 1537–1540. https://doi.org/10.1126/science.1137695.

Lenton, T.M., J. Rockstöm, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and J.H. Schnellnhber. 2019. Climate tipping points—Too risky to bet against. *Nature* 575: 592–595.

Leopold, A. 1949. *A Sand County almanac, and Sketches here and there*. New York: Oxford University Press.

Lin, Z., L. Chen, X. Chen, Y. Zhong, Y. Yang, W. Xia, C. Liu, W. Zhu, et al. 2019. Biological adaptations in the Arctic cervid, the reindeer (*Rangifer tarandus*). *Science* 364: 6446.

Littell, J.S., S.A. McAfee, and G.D. Hayward. 2018. Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. Water 10: 668 https://www.mdpi.com/2073-4441/10/5/668. Accessed 17 June 2021.

Locke, H., E.C. Ellis, O. Venter, R. Schuster, K. Ma, X. Shen, S. Woodley, N. Kingston, et al. 2019. Three global conditions for biodiversity conservation and sustainable use: An implementation framework. *National Science Review* 6: 1080–1082. https://doi.org/10.1093/nsr/nwz136.

Lynch, A.J., L.M. Thompson, J.M. Morton, E.A. Beever, M. Clifford, D. Limpinsel, R.T. Magill, D.W. Magness, et al. 2022. RAD adaptive management for transforming ecosystem. *BioScience* 72: 45–56. https://doi.org/10.1093/biosci/biab091.

Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, et al. 2018. Alaska. In *Impacts, risks, and adaptation in the United States: Fourth national climate assessment*, ed. D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, B.C. Stewart, vol. II, 1185–1241. Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH26.

McGarigal, K., B.W. Compton, E.B. Plunkett, W.V. DeLuca, J. Grand, E. Ene, S.D. Jackson. 2018. A landscape index of ecological integrity to inform landscape conservation. *Landscape Ecology* 33: 1029–1048. https://doi.org/10.1007/s10980-018-0653-9.

McLennan, D.S., W.H. MacKenzie, D. Meidinger, J. Wagner, and C. Arko. 2018. A standardized ecosystem classification for the coordination and design of long-term terrestrial ecosystem monitoring in Arctic–sub-Arctic biomes. *Arctic* 71: 1–15.

Meffe, G.K., C.R. Carroll, and M.J. Groom. 2006. *What is conservation biology? Principles of conservation biology*, 4th ed. Sunderland: Sinauer & Associates.

Millennium Ecosystem Assessment. 2005. https://www.millenniumassessment.org/en/Index-2.html. Accessed 17 June 2021.

National Park Service (NPS). 2006. *Management policies 2006*. ISBN 0-16-076874-8. https://www.nps.gov/orgs/1548/upload/ManagementPolicies2006.pdf. Accessed 17 June 2021.

National Resource Council. 2014. *The Arctic in the Anthropocene: Emerging research questions*. Washington, DC: National Academies Press.

Osborne, E., J. Richter-Menge, and M. Jeffries 2018. *Arctic Report Card 2018*. https://www.arctic.noaa.gov/Report-Card. Accessed 17 June 2021.

Parrish, J.D., D.P. Braun, and R.S. Unnasch. 2003. Are we conserving what we say we are? Measuring ecological integrity within protected areas. *BioScience* 53: 851–860.

Redford, K., and M.A. Sanjayan. 2003. Retiring Cassandra. *Conservation Biology* 17: 1473–1474.

Reynolds, J.H., E.J. Trammell, and J.J. Taylor. 2018. *Migration's foundation: Ecological intactness of Alaska's ecosystems*. Alaska Park Science. https://www.nps.gov/articles/aps-17-1-13.htm. Accessed 17 June 2021.

Rohwer, Y., and E. Marris. 2021. Ecosystem integrity is neither real nor valuable. *Conservation Science and Practice* 3: 1–11. https://doi.org/10.1111/csp2.411.

Rybicki, J., and I. Hanski. 2013. Species–area relationships and extinctions caused by habitat loss and fragmentation. *Ecology Letters* 16: 27–38. https://doi.org/10.1111/ele.12065.

Sanderson, L.A., J.A. Mclaughlin, and P.M. Antunes. 2012. The last great forest: A review of the status of invasive species in the North American boreal forest. *Forestry: An International Journal of Forest Research* 85: 329–340. https://doi.org/10.1093/forestry/cps033.

Schmidt, N.M., J.B. Mosbacher, P.S. Nielsen, C. Rasmussen, T.T. Høye, and T. Roslin. 2016. An ecological function in crisis? The temporal overlap between plant flowering and pollinator function shrinks as the Arctic warms. *Ecography* 39: 1250–1252.

Schmidt, N.M., B. Hardwick, O. Gilg, T.T. Høye, P.H. Krogh, H. Meltofte, A. Michelsen, J.B. Mosbacher, et al. 2017. Interaction webs in Arctic ecosystems: Determinants of Arctic change? *Ambio* 46: S12–S25. https://doi.org/10.1007/s13280-016-0862-x.

Schmidt, N.M., J. Reneerkens, J.H. Christensen, M. Olesen, and T. Roslin. 2019. An ecosystem-wide reproductive failure with more snow in the Arctic. *PLoS Biology* 17: e3000392.

Schmiegelow, F.K.A., S.G. Cumming, K.A. Lisgo, S.J. Leroux, and M.A. Krawchuk. 2014. Catalyzing large landscape conservation in Canada's boreal systems: The BEACONs project experience. In *Conservation catalysts*, ed. J.N. Levitt, 97–122. Cambridge: Lincoln Institute of Land Policy, Harvard Press.

Schuurman, G.W., D.N. Cole, A.E. Cravens, S. Covington, S.D. Crausbay, C.H. Hoffman, D.J. Lawrence, D.R. Magness, et al. 2021. Navigating ecological transformation: Resist–accept–direct as a path to a new resource management paradigm. *BioScience*. https://doi.org/10.1093/biosci/biab067.

Tallis, H., C.M. Kennedy, M. Ruckelshaus, J. Goldstein, and J.M. Kiesecker. 2015. Mitigation for one and all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services. *Environmental Impact Assessment Review* 55: 21–34. https://doi.org/10.1016/j.eiar.2015.06.005.

Taylor, J.J., D.G. Brown, and L. Larsen. 2007. Preserving natural features: A GIS-based evaluation of a local open-space ordinance. *Landscape and Urban Planning* 82: 1–16. https://doi.org/10.1016/j.landurbplan.2007.01.013.

Taylor, J.J., C.A. Lepczyk, and D.G. Brown. 2016. Patch and matrix level influences on forest birds at the rural–urban interface. *Landscape Ecology* 31: 1005–1020. https://doi.org/10.1007/s10980-015-0310-5.

Taylor, J.J., J.P. Lawler, M. Aronsson, T. Barry, A.D. Bjorkman, T. Christensen, S.J. Coulson, C. Cuyler, et al. 2020. Arctic terrestrial biodiversity status and trends: A synopsis of science supporting the CBMP State of Arctic Terrestrial Biodiversity Report. *Ambio* 49: 833–847. https://doi.org/10.1007/s13280-019-01303-w.

Theobald, D.M. 2013. A general model to quantify ecological integrity for landscape assessments and US application. *Landscape Ecology* 28: 1859–1874. https://doi.org/10.1007/s10980-013-9941-6.

Trammell, E.J., and M. Aisu 2015. *Development of a landscape integrity dataset for the Alaska crucial habitat assessment tool*. Prepared for the Alaska Department of Fish and Game. Anchorage: University of Alaska. https://accs.uaa.alaska.edu/wp-content/uploads/CHAT_LI_Final_Report.pdf. Accessed 17 June 2021.

Trammell, E.J., T. Boucher, M.L. Carlson, N. Fresco, J.R. Fulkerson, M.L. McTeague, J. Reimer, and J. Schmidt. 2016. *Central Yukon Rapid Ecoregional Assessment Final Report*. Denver: US Department of the Interior, Bureau of Land Management.

Turner, M.G., R.H. Gardner, and R.V. O'Neill. 2001. *Landscape ecology in theory and practice: Pattern and process*. New York: Springer.

Tyler, N.J.C. 2010. Climate, snow, ice, crashes, and declines in populations of reindeer and caribou (*Rangifer tarandus* L.). *Ecological Monographs* 80: 197–219. https://doi.org/10.1890/09-1070.1.

USGCRP. 2018. In *Second state of the carbon cycle report (SOCCR2): A sustained assessment report*, ed. N. Cavallar, G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu. U.S. Global Change Research Program, Washington, DC: USGCRP. https://doi.org/10.7930/SOCCR2.2018.

Venter, O., E.W. Sanderson, A. Magrach, J.R. Allan, J. Beher, K.R. Jones, H.P. Possingham, W.F. Laurance, et al. 2016. Global terrestrial Human Footprint maps for 1993 and 2009. *Scientific Data* 3: 160067. https://doi.org/10.1038/sdata.2016.67.

Walker, X.J., J.L. Baltzer, S.G. Cumming, N.J. Day, C. Ebert, S. Goetz, J.F. Johnstone, S. Potter, et al. 2019. Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* 572: 520–523. https://doi.org/10.1038/s41586-019-1474-y.

Walston, L.J., and H.M. Hartmann. 2018. Development of a landscape integrity model framework to support regional conservation planning. *PLoS ONE* 13: e0195115. https://doi.org/10.1371/journal.pone.0195115.

Wasowicz, P., A.N. Sennikov, K.B. Westergaard, K. Spellman, M. Carlson, L.J. Gillespie, J.M. Saarela, S.S. Seefeldt, et al. 2020. Non-native vascular flora of the Arctic: Taxonomic richness, distribution and pathways. *Ambio* 49: 693–703. https://doi.org/10.1007/s13280-019-01296-6.

Wilson, R.E., S.D. Farley, T.J. McDonough, S.L. Talbot, and P.S. Barboza. 2015. A genetic discontinuity in moose (*Alces alces*) in Alaska corresponds with fenced transportation infrastructure. *Conservation Genetics* 16: 791. https://doi.org/10.1007/s10592-015-0700-x.

Wilson, R.R., L.S. Parrett, K. Joly, and J.R. Dau. 2016. Effects of roads on individual caribou movements during migration. *Biological Conservation* 195: 2–8. https://doi.org/10.1016/j.biocon.2015.12.035.

Wurtzebach, Z., and C. Schultz. 2016. Measuring ecological integrity: History, practical applications, and research opportunities. *BioScience* 66: 446–457. https://doi.org/10.1093/biosci/biw037.

AUTHOR BIOGRAPHIES

E. Jamie Trammell (✉) is an Associate Professor and Chair of Environmental Science at Southern Oregon University and affiliate of the Alaska Center for Conservation Science. His research centers on modeling landscape change with an explicit focus on the integration of socioeconomic and biophysical drivers using GIS.
Address: Alaska Center for Conservation Science, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508, USA.
Address: Environmental Science, Policy, & Sustainability, Southern Oregon University, 1250 Siskiyou Blvd., Ashland, OR 97520, USA.
e-mail: trammelle@sou.edu; ejtrammell@alaska.edu

Matthew L. Carlson is a Director of the Alaska Center for Conservation Science at the University of Alaska Anchorage. His research interests include plant ecology and evolution and biological conservation in Alaska and the circum-Arctic.
Address: Alaska Center for Conservation Science, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508, USA.
e-mail: mlcarlson@alaska.edu

Joel H. Reynolds is a Climate Science and Adaptation Coordinator at the US National Park Service's Climate Change Response Program. His research interests include climate change adaptation in protected area management, landscape conservation, and statistical issues in natural resource monitoring.
Address: Climate Change Response Program, U.S. National Park Service, 1201 Oakridge Dr. Suite 200, Fort Collins, CO 80525, USA.
e-mail: joel_reynolds@nps.gov

Jason J. Taylor is a Landscape Ecologist and Director of the Aldo Leopold Wilderness Research Institute. In addition to many years of leading protected areas management and science programs, Jason has an extensive background in the application of geospatial technologies. His research efforts have focused on landscape ecology, ecological integrity, and multi-scale monitoring programs across the American West, Alaska, and the circumpolar Arctic.
Address: Aldo Leopold Wilderness Research Institute, USDA Forest Service, Rocky Mountain Research Station, 790 E. Beckwith Ave, Missoula, MT 59801, USA.
e-mail: jason.taylor2@usda.gov

Niels M. Schmidt is a Professor in Arctic ecology. His research mainly focuses on the importance of biotic interactions in the rapidly changing Arctic.
Address: Department of Ecoscience, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark.
e-mail: nms@ecos.au.dk