Designing NEON Initiatives for Invasive Species

Report from a NEON Science Workshop

March 18, 2004
Washington, DC

neon
National Ecological Observatory Network

American Institute of Biological Sciences

IBRCS
Infrastructure for Biology at Regional to Continental Scales
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The IBRCS Program

The Infrastructure for Biology at Regional to Continental Scales (IBRCS) Program, an effort by the American Institute of Biological Sciences (AIBS), launched in August 2002 with support from the National Science Foundation. The following are the program's goals:

- Help the biological and the larger scientific community—within and beyond the AIBS membership—to determine the needs and means for increased physical infrastructure and connectivity in observational platforms, data collection and analysis, and database networking in both field biology and other more general areas of biology and science.
- Provide for communications within this community and with NSF regarding the development and focus of relevant infrastructure and data-networking projects.
- Facilitate the synergistic connection of diverse researchers and research organizations that can exploit the power of a large-scale biological observatory program.
- Disseminate information about biological observatory programs and other relevant infrastructure and data-networking projects to the scientific community, the public policy community, the media, and the general public.

The program is led by a working group comprising biologists elected from the AIBS membership of scientific societies and organizations and appointed from the scientific community at-large. It is assisted by a variety of technical advisors. The program has a special focus on the National Ecological Observatory Network (NEON), which is a major NSF initiative to establish a national platform for integrated studies and monitoring of natural processes at all spatial scales, time scales, and levels of biological organization. Jeffrey Goldman, PhD, is the Director of the IBRCS program. He and Richard O'Grady, PhD, AIBS Executive Director, are co-principal investigators under the grant. Additional information is available at *http://ibrcs.aibs.org*.

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About the American Institute of Biological Sciences

The American Institute of Biological Sciences is a non-profit(c)(3) scientific organization of more than 6,000 individuals and 86 professional societies. AIBS performs a variety of public and membership services, which include publishing the science magazine, BioScience, convening meetings, and conducing scientific peer review and advisory services for government agencies and other clients.

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This document is available from:

American Institute of Biological Sciences
1444 I Street, NW, Suite 200
Washington, DC 20005
tel. 202-628-1500
fax 202-628-1509
mbrown@aibs.org

This document is also available online at *http://ibrcs.aibs.org*.

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NEON Workshop Series

The National Ecological Observatory Network (NEON) is a major initiative proposed by the National Science Foundation (NSF) to establish a continental-scale platform for integrated studies on natural processes at all spatial scales, time scales, and levels of biological organization. NEON is anticipated to provide the resources and infrastructure for fundamental biological research that will enhance our understanding of the natural world, improve our ability to predict the consequences of natural and anthropogenic events, and inform our environmental decision-makers.

The previous two years of NEON-related activity have revealed several steps that the scientific community must take along the path to the creation of NEON. Prior work showed that in order to develop a detailed description of NEON's physical design, an important milestone for NEON, the scientific objectives and targets of NEON must first be defined. With this in mind, as part of the NSF-funded Infrastructure for Biology at Regional to Continental Scales (IBRCS) project, AIBS, in partnership with experts from the prospective NEON community, convened a series of workshops between March and September, 2004, focused on the following ecological themes, which have been proposed as guideposts for the design of NEON:

- Ecological implications of climate change
- Land use and habitat alteration
- Invasive species
- Biodiversity, species composition, and ecosystem functioning
- Ecological aspects of biogeochemical cycles
- Ecology and evolution of infectious disease

The goal of the workshops was to highlight urgent scientific questions that NEON can address, define science requirements associated with those questions, assess the state of currently available infrastructure, and discuss needs for future infrastructure development. The recommendations that grew from these meetings, as captured in this report and others in the series, will guide subsequent NEON planning.

This workshop series opened up the NEON planning process to a diverse group of scientists from academia, government, and the NGO community. In total more than 120 scientists participated in these meetings—some were previously involved in NEON activities, while others took part in a NEON effort for the first time.

Introduction

Recently, the National Science Foundation announced its intention to support the establishment of a national coordinating organization for the National Ecological Observatory Network (NEON). Among the goals of the NEON Coordinating Consortium will be to define the scientific scope and technical requirements of NEON and create an implementation plan. Although the broad-brushstroke design of NEON—a network of spatially distributed and highly integrated research facilities, connected by a cyberinfrastructure—has been identified (AIBS 2003), specific details must be defined more precisely.

To define the details, it is valuable first to consider which broad ecological issues may be best addressed by a distributed research platform, such as NEON, and subsequently let the science guide the detailed design of the network. Several broad research challenges of national concern already have been identified (NRC 2001, 2003). These include biodiversity, species composition, and ecosystem functioning; ecological aspects of biogeochemical cycles; ecological implications of climate change; ecology and evolution of infectious diseases; land use and habitat alteration; and invasive species. A workshop was convened in March to focus on the design of NEON in relation to invasive species, and this report presents its recommendations. Three unresolved, high-priority issues in invasive species research surfaced, and research priorities and scientific requirements were identified for each. Using the guidelines established by the workshop participants, key aspects of NEON's design emerged and are described below.

Criteria for Setting Research Priorities

To distill a manageable number of high-priority issues in invasive species research from the pool of possibilities, the following criteria, reflecting the broad goals and general design of NEON (AIBS 2003), were applied. The research areas of highest priority are those that:

- Enable the discovery of general principles (in preference to species-specific or site-specific solutions to problems).
- Have to date been intractable due to current research infrastructure limitations and thus will benefit from advances in methodology or technology.
- Require multiple, integrated research sites spread across the nation.
- Will complement, rather than duplicate or compete with, existing programs focused on invasive species.

If the design of NEON follows from research topics that meet these criteria, NEON will enable scientific inquiry on pressing invasion issues at scales (regional and continental) previously unattainable with existing research programs.

High-priority Issues in Invasive Species Science

Unanticipated invasions of species impact human health, welfare, and quality of life in ways that are only sometimes visible and apparent but are almost always detrimental economically and ecologically (Pimentel *et al*. 2000). Thus, it is surprising that many fundamental aspects of invasive species biology, ecology, and economics are not well understood. Our knowledge gaps are evident primarily in our inability to determine which species will become invasive, predict the spread of species, and understand the impacts of invasive populations across community types, among ecoregions, and over time.

While single-species or local habitat–focused research on invasions has generated some solutions, those solutions tend to apply only locally and over limited time scales. The lack of more comprehensive information for use by managers, policy makers, and other decisionmakers can result in a "reinvention of the wheel" for each new species and habitat of concern. Because invaders are often cosmopolitan and move from one community type to another, invasive species are a long-term, continental-scale, multi-species problem. Consequently, we must develop a comparative approach to the theory of invasive species biology that will allow us to address fundamental questions at appropriate spatial and temporal scales. NEON is poised to make significant contributions to this line of research.

Using the criteria for setting research priorities noted above, three critical issues within the topic of invasive species were identified to guide discussions and recommendations about NEON's design: (a) the invasion characteristics of diverse taxa, including plants, animals, and microbes; (b) the invasibility of different biomes in the United States, such as deserts, forests, and grasslands; and (c) the consequences of invasions on ecosystem structure and function and delivery of ecosystem services.

In each of these three areas, issues of spatial and temporal scale must be explicitly addressed in the research. Replicating measurements and experiments across a continental network is not simply a matter of repeating the same thing in many places. Rather, an integrated network will allow scientists to explore how varying ecological factors operate at different scales with coordinated and concurrent research. For example, the factors that promote the establishment of an invasive species within a particular study plot may be entirely different from those factors that allow the species to spread from one part of a region to another or among ecoregions. Because NEON will be designed for measurements at multiple spatial and temporal scales, ecologists will have the ability to determine for the first time how nested ecological processes influence the establishment and spread of invasive species.

Traits, syndromes, and spread of invasive species. Debate continues on whether there exist common traits that identify species as invasive. When such debates persist in ecology, they are usually the result of data limitations and narrowly focused studies that fail to provide the broad base of information from which more general theory can emerge. Even if the traits that favor invasive species in one habitat type are different from those that favor invasion in another, this hypothesis cannot be tested by the single-species and local focus of current invasive species programs. Rather, the distributed network provided by NEON will allow explicit consideration of habitat-specific and region-specific traits that favor invasion.

Moreover, ecologists have barely begun to consider differences (or similarities) among the invasion syndromes of plants, animals, and microbes. Included within these groups, are organisms that affect the health of humans, crops, livestock, and wildlife. No theory currently exists to help us explore the factors that control rates of spread of these different invaders and predict their likely success in different habitats and ecoregions. Essential to the development of such theory will be continental-scale monitoring of the traits of invasive species and their rates of spread from one ecoregion to the next, including distribution information correlated to abiotic factors. The ability to predict how some organisms (particularly pathogens) migrate from one region to another via other species, or by human activity, will require coordinated interdisciplinary measurements of multiple species at large spatial scales over time.

What makes a species and a population invasive?

- Are there invasion characteristics of taxa that are useful for predicting invasions?
- Can we identify traits that permit species or populations to invade regions? For example, are wind-dispersed species more prone to invade than non-wind-dispersed species?
- Can we identify genetic signatures in populations that correlate with the likelihood of invasion?

Invasibility of communities. Recent theoretical approaches to the study of invasibility have stressed spatial and temporal variation in resource supply and demand (Davis, *et al*. 2000, Shea and Chesson 2002, Davis 2003). The probability of invasion is predicted to increase whenever resource use by the local community is less than resource supply. The difference between resource supply and demand will obviously vary from one community to the next and within one community over time. Yet we have no current way of predicting whether ecoregions vary consistently in their susceptibility to invasion or if the susceptibility of systems can be altered to lower the incidence of invasion. Nor do we know whether similar temporal patterns of susceptibility occur from one habitat to the next.

The distributed network of observations and experiments provided by NEON will allow us to employ a powerful comparative approach to studying community invasions. Among other things, we will be able to answer the fundamental questions related to how propagule pressure, ecoregion, community type, anthropogenic factors, and resource supply and their interactions influence invasibility. With a platform for coordinated experimental manipulations and standard measurements, ecologists will develop the first understanding of if, how, and why grasslands, forests, deserts, and streams differ in their invasibility. Using infrastructure designed to monitor resource supply and demand in real time, we will be able to assess temporal variation in susceptibility to invasion. And using a national network of spatially explicit relational databases, ecologists will be able to map and forecast invasions in space and time.

Are there general characteristics of ecosystems that make them vulnerable to invasions?

- Which ecosystems are most vulnerable to invasion?
- How does land-use history influence invasibility?
- What are the abiotic and biotic factors that determine whether an invasion is likely to take place?
- What are the temporal determinants of invasion?
- What are the spatial scale dependencies between native species abundances and invasive species abundances?
- Do invasions in one trophic group contribute to invasions of other trophic groups?

Ecosystem structure and function. Ecologists have spent considerable effort quantifying the consequences of invasions for ecosystems and still cannot currently forecast how species invasions influence the structure and function of ecosystems. While alterations in ecosystem services, losses of native species, and declines in biodiversity sometimes result from invasion, the causes and consequences of such losses are not mechanistically understood. For example, it has been suggested that most species losses that result from invasion are the product of predator–prey interactions rather than competition (Davis 2003). Only long-term, continent-wide observations will allow us to test the generality of this and other theories and ultimately to predict the consequences of specific invasion events. NEON will include a distributed network of sites in which community and ecosystem responses to the invasion of predators, parasites, pathogens, and competitors are evaluated. By co-locating invasive species observatory sites with those for studying biodiversity and ecosystem function we will be able to develop general theories relating biodiversity to ecosystem structure and function and determine the role that invasive species play in changing this relationship over time.

Key to these three invasion research issues is the emergence of a comparative approach to invasive species biology. The NEON network will promote comparisons of (a) different invasive species taxa, (b) invasions in different ecoregions or biomes, and (c) scales of pattern and process within and among NEON facilities. The comparative approach is a prerequisite for conceptual synthesis and development of theory and general principles in a discipline that has a history of single-species or single-problem research projects. The comparative approach will be fostered by both the design of NEON facilities and the seamless integration of data through networked cyberinfrastructure.

What are the consequences of invasions on ecosystem structure and function?

- How do outcomes of invasions depend on traits of the invader and the environmental context of the invasion?
- How do changes propagate through levels of ecosystems? Are they dampened or amplified and what controls the balance?
- What is the relative threat posed by "competition" (e.g., plant invader impacts on plants) compared to threats due to "predation" (e.g., plant–herbivore or predator–prey interactions)?
- Under what conditions are invasion effects reversible?
- What are the rates of recovery from an invasion?

<u>Connection between invasive species issues and other topics</u>. Although the six broad ecological topics that have been recommended for NEON are listed, and in some cases considered, separately, they all interact to some degree and cannot be treated independently.

The biodiversity, species composition, and ecosystem functioning theme is, in many ways, a parent topic to invasive species because questions regarding causes and consequences of invasions are a subset of similar questions to be asked about patterns influencing the abundance, distribution, and ecosystem services provided by biodiversity. Similarly, biogeochemistry is viewed as both a driver and response function relative to invasive species analyses; invasions are affected by resource availability, and changes in biotic composition may or may not induce biogeochemical changes. Land use and habitat alteration and climate change are seen as drivers of invasions and facilitators of the movement of invasive species. Under certain scenarios, change brought by invasive species may be sufficiently extensive to alter climate (e.g., C_3 to C_4 conversions or vice versa). The ecology and evolution of infectious diseases challenge is a subset of the invasive species initiative, but one that is of such important societal concern as to be considered separately.

Because the overlap among these topics is substantial, careful design of the NEON research platform will enable ecologists to comprehensively analyze invasions in the context of these other contributing factors and can help explain both the extent to which invasions are consequences of other global change drivers and how the consequences of invasions, such as their effects on ecological services, are functions of the biota rather than other variables.

Scientific Requirements

To make progress in our understanding of invasive species issues, emphasis must be placed on the development of invasion theory that can be used to predict vunlerabilities and respond to invasion events. The issues described above suggest that to achieve this objective, NEON must meet several infrastructure requirements, among the most pressing of which are:

- Infrastructure to enable the monitoring of the current distribution of invasions and the detection of spatial and temporal dynamics. Spatially explicit databases of population numbers layered with climatological, topographical, and edaphic data are an essential component of NEON.
- Experimental infrastucture to generate a mechanistic understanding of invasive species dynamics. Replicated experimental units, within and among regions, will explore the impacts of disturbance, resource supply, and local environment on invasion dynamics.
- Modeling tools to forecast invasive species interactions, correlate them with other environmental changes, and integrate social and economic factors. Modeling tools will span the range from fine-scale, individual-based models of single populations to large-scale, climatological models that explore continental scale processes that operate during invasions.
- Archives of specimens and data with protocols for their use. Both physical and virtual collections will be required to document temporal changes in communities and to act as repositories of genetic, physiological, and morphological data.
- Cyberinfrastructure to enable the above and to integrate and disseminate acquired information.

One potential implementation scheme includes replicating (a) a regional monitoring array, (b) an experimental array facility, and (c) an informatics and modeling facility in the major ecosystems of the nation. These three elements are briefly described below.

(a) A regional monitoring array will be important for assessing spatial distributions of invasive species populations annually. Such an array will be based on spatially and temporally relevant climatic, edaphic, and biotic factors and corresponding land-use and land-management habitat types, as well as key social and economic drivers. Specifications include:

- Permanent monitoring sites linked with extant programs
- Annual regional censuses of invasive species populations
- Inter- and intra-regional coordination in sampling protocols
- Periodic sampling and archiving

(b) An experimental array facility will be invaluable for identifying underlying mechanisms determining invasion; for helping scientists capture key environmental and socio-economic gradients across regions; for providing supporting laboratory, greenhouse, and microcosm studies; and for supporting synoptic measurement of core genetic, organismal, population, community, and ecosystem responses. Specifications include:

- Coordinated manipulative experiments across key gradients
- Centralized greenhouses, terrestrial and aquatic mesocosms, and controlled environmental facilities
- Supporting lab facilities including analytical and genomic instrumentation and cyberinfrastructure
- Archival facilities

(c) An informatics and modeling facility will provide the tools and arena for data management, integration, and synthesis. Specifications include:

- Computational capacity
- Networking and data storage capacity
- Technical and logistical support for modeling and synthesis activities

In many cases, these facilities and arrays can co-exist with or build upon existing facilities and programs. The result, however, would far exceed any existing capabilities because of the comprehesive nature of the coverage as well as the standardization and coordination built into the system. In addition, requirements for NEON infrastructure should stimulate partnerships between information technologists and environmental biologists. Furthermore, because requirements for invasive species research overlap with requirements for other NEON topic areas, the infrastructure described above is envisioned to be co-located with additional infrastructure for other NEON themes. In this way, the important interactions between the topics can be explored and economies of scale can be realized.

Next Steps

Because of the scale of NEON and its potential for facilitating research on a large number of overlapping ecological topics, NEON is poised to promote comparative studies and theory development on invasive species issues. The NEON workshop on invasive species initiatives was an initial effort to link research questions with design features in order to determine NEON's scientific and technological requirements. The process of designing NEON is necessarily iterative. Therefore, these recommendations are a first step toward refining NEON's design plans. Subsequent work will further distill the scientific questions to be pursued with the network and refine them in light of overlapping requirements for different ecological themes, in order to develop a more detailed picture of NEON's eventual design.

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Workshop Participants

Ann Bartuska
USDA Forest Service
Research and Development
1 NW Yates Bldg
1400 Independence Ave. SW
Washington, DC 20250-1120
P: 202-205-1665
F: 202-205-1530
E: abartuska@fs.fed.us

Faith Campbell
The Nature Conservancy
4245 North Fairfax Drive, Suite 100
Arlington, VA 22203
P: 703-841-4881
F: 703-841-1283
E: fcampbell@tnc.org

Julie Coonrod
Department of Civil Engineering
MSC 01 1070
1 University of New Mexico
Albuquerque, NM 87131-0001
P: 505-277-3233
E: jcoonrod@unm.edu

Joel L. Cracraft
Division of Vertebrate Zoology - Ornithology
American Museum of Natural History
Central Park West @ 79th Street
New York, NY 10024-5192
P: 212-769-5633
F: 212-769-5759
E: jlc@amnh.org

Chris Dionigi
National Invasive Species Council
1201 Eye Street, N.W. Room 71, Floor 5
Washington, DC 20005
202-513-7245
P: 202-354-1876
F: 202-371-1751
E: Chris_Dionigi@IOS.DOI.gov

David Cameron Duffy
Pacific Cooperative Studies Unit (PCSU)
University of Hawai'i
3190 Maile Way St. John 410
Honolulu, HI 96822-2279
P: 808-956-8218
F: 808-973-2936
E: dduffy@hawaii.edu

Clifford S. Duke
Ecological Society of America
1707 H Street NW, Suite 400
Washington DC 20006
P: 202-833-8773 ext. 202
F: 202-833-8775
E: csduke@esa.org

Virginia Ferris
Purdue University
1158 Smith Hall
West Lafayette, IN 47907
P: 756-494-4609
F: 756-494-0535
E: vferris@entm.purdue.edu

Deborah Goldberg
Department of Ecology and Evolutionary Biology
The University of Michigan
Natural Science Building (Kraus)
830 North University
Ann Arbor, MI 48109-1048
P: 734-764-1490
F: 734-647-0884
E:degold@umich.edu

Claus Holzapfel
Rutgers University
Dept. of Biological Sciences
101 Warren Street
Newark, NJ 07102-1811
P: 973-353 5385 (temp.)
F: 973-353 5518
E: holzapfe@andromeda.rutgers.edu

Mark D. Hunter
Center for Biodiversity and Ecosystem Processes
Institute of Ecology
University of Georgia
Athens, GA 30602-2202
P: 706-542-1801
F: 706-542-4819
E: mdhunter@uga.edu

Alan K. Knapp
Department of Biology
Colorado State University
Ft. Collins, CO 80523
P: 970-491-7010
F: 970-491-0649
E: aknapp@lamar.colostate.edu

Richard N. Mack
School of Biological Sciences
Washington State University
Pullman, WA 99164
P: 509-335-3316
F: 509-335-3184
E: rmack@mail.wsu.edu

Laura Meyerson
The Heinz Center
1001 Pennsylvania Avenue, N.W.
Suite 735 South
Washington, DC 20004
P: 202-737-6307
F: 202-737-6410
E: meyerson@heinzctr.org

Rachel Claire Muir
U.S. Geological Survey
John Wesley Powell, MS 301
12201 Sunrise Valley Drive
Reston, VA 20192
P: 703-648-5000
F: 703-648-5295
E: rachel_muir@usgs.gov

Pamela O'Neil
Office of Research and Sponsored Projects
CERM Building, Suite 422
University of New Orleans
2045 Lakeshore Drive
New Orleans, LA 70148
P: 504-280-7042
F: 504-280-3896
E: poneil@uno.edu

Richard Orr
National Invasive Species Council
DOI - OS - SIO
1849 C Street N.W.
Washington D.C. 20240
P: 202-354-1882
F: 202-371-1751
E: richard_orr@ios.doi.gov

Townsend Peterson
Department of Ecology and Evolutionary Biology
Curator of Ornithology
Natural History Museum and Biodiversity Research Center
The University of Kansas
Lawrence, KS 66045
P: 785-864-3926
F: 785-864-5335
E: town@ku.edu

George Roderick
UCB Gump South Pacific Research Station
Essig Museum of Entomology
201 Wellman Hall MC 3112
University of California
Berkeley, CA 94720-3112
P: 510-643-3326
F: 510-642-7428
E: roderick@berkeley.edu

Tim Seastedt
Ecology and Evolutionary Biology
INSTAAR, CB 450
University of Colorado
Boulder, CO 80309-0450
P: 303-492-3302
F: 303-492-6388
E: Timothy.Seastedt@Colorado.EDU

David C. Shaw
Wind River Canopy Crane Research Facility
University of Washington
1262 Hemlock Road
Carson, WA 98610
P: 509-427-7028
F: 509-427-7037
E: dshaw@u.washington.edu

John Silander
Ecology and Evolutionary Biology
University of Connecticut
Storrs, CT 06269-3043
P: 860-486-2168
F: 860-486-6364
E: john.silander@uconn.edu

Melinda D. Smith
Yale University
Dept. of Ecology and Evolutionary Biology
P.O. Box 208106
New Haven, CT 06520-8106
P: 203-432-9422
F: 203-432-5176
E: melinda.smith@yale.edu

Bruce A. Stein
NatureServe
1101 Wilson Boulevard
15th Floor
Arlington, VA 22209
P: 703-908-1830
F: 703-908-1917
E: bruce_stein@natureserve.org

Kristina A. Stinson
Harvard University-Harvard Forest
PO Box 68
Petersham, MA 01366
P: 978-724-3302 ext. 284
E: kstinson@oeb.harvard.edu

Geraldine W. Twitty
Biology Department
Ernest Just Hall (Biology)
Howard University
Washington, DC 20059
P: 202-806-6953
E: gtwitty@howard.edu

Fernando E. Vega
Insect Biocontrol Laboratory
United States Department of Agriculture
Agricultural Research Service
Building 011A, BARC-WEST
10300 Baltimore Ave.
Beltsville, MD 20705
P: 301-504-5101
F: 301-504-5104
E: vegaf@ba.ars.usda.gov

Randy Westbrooks
U.S. Geological Survey
Biological Resources Discipline
233 Border Belt Drive, P.O. Box 279
Whiteville, NC 28472
P: 910-648-6762
F: 910-648-6763
E: rwestbrooks@usgs.gov

Workshop Observers

Elizabeth R. Blood
Program Director
National Ecological Observatory Network (NEON)
Division of Biological Infrastructure
National Science Foundation
4201 Wilson Blvd #615N
Arlington, VA 22230
P: 703-292-8470
E: eblood@nsf.gov

Dylan George
National Ecological Observatory Network (NEON)
Division of Biological Infrastructure
National Science Foundation
4201 Wilson Blvd #615N
Arlington, VA 22230
P: 703-292-8470
E: dgeorge@nsf.gov

AIBS Staff

Jeffrey Goldman
American Institute of Biological Sciences
1444 I Street, NW
Suite 200
Washington, DC 20005
P: 202-628-1500 X 225
F: 202-628-1509
E: jgoldman@aibs.org

Rina Aviram
American Institute of Biological Sciences
1444 I street, NW
Suite 200
Washington, DC 20005
P: 202-628-1500 X 231
F: 202-628-1509
E: raviram@aibs.org

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