Ecological science and sustainability for the 21st century

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Ecological science has contributed greatly to our understanding of the natural world and the impact of humans on that world. Now, we need to refocus the discipline towards research that ensures a future in which natural systems and the humans they include coexist on a more sustainable planet. Acknowledging that managed ecosystems and intensive exploitation of resources define our future, ecologists must play a greatly expanded role in communicating their research and influencing policy and decisions that affect the environment. To accomplish this, they will have to forge partnerships at scales and in forms they have not traditionally used. These alliances must act within three visionary areas: enhancing the extent to which decisions are ecologically informed; advancing innovative ecological research directed at the sustainability of the planet; and stimulating cultural changes within the science itself, thereby building a forward-looking and international ecology. We recommend: (1) a research initiative to enhance research project development, facilitate large-scale experiments and data collection, and link science to solutions; (2) procedures that will improve interactions among researchers, managers, and decision makers; and (3) efforts to build public understanding of the links between ecosystem services and humans.

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In the fall of 2002, the Ecological Society of America (ESA) established a committee to develop an action plan for bolstering the research capabilities and impact of the ecological sciences. After much work and with substantial input from many people within and beyond the Society, the committee delivered a report to the ESA Governing Board in April 2004. This article is a brief summary of recommended actions that must be taken, by members of the scientific community and others, to produce the knowledge, discoveries, and forms of communication that will ensure that ecology effectively informs decisions that influence environmental sustainability globally. The full report is available at www.esa.org/ecovisions.

In a nutshell:

- Ecological science can and must play a greatly expanded role in ensuring a future in which natural systems and the human populations they include exist on a more sustainable planet
- Implementation of a bold, proactive action plan for ecological science will generate the necessary knowledge to conserve, restore, and design the world's ecological systems
- Ecologists must act now to inform decisions with ecological knowledge; advance innovative and anticipatory ecological research directed at sustainability; and stimulate cultural changes that facilitate a forward-looking and international ecology

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For much of the past century, ecologists have enhanced our understanding of nature by focusing on the least disturbed ecosystems on earth. This has generated tremendous insights into complex ecological interactions and has positioned ecologists to focus on the impacts of humans on the planet. A more recent body of research treats humans as one of many components of ecosystems – humans are seen not only as exploiters of ecosystem services, but as agents of change who are themselves influenced by this change (Povilitis 2001; Turner *et al.* 2003). This makes sense because all organisms modify the environment in which they live; certainly humans differ in the extent to which they transform their surroundings, but they also have the ability to forecast and modify their behaviors in anticipation of tomorrow's changes.

Within the discipline of ecology, our thinking has thus evolved from a focus on humans as intruders on the natural world to humans as part of the natural world (Botkin 1990; Blondel and Vigne 1993; McDonnell and Pickett 1993; Redman 1999). Now, however, ecologists must go much further and focus on how humans can exist in a *more sustainable* natural world. We do not deny the devastating impacts humans have had on the earth – indeed, these impacts are present in the air we breathe, the water we drink, and in the land that we depend on for food and habitat (Vitousek *et al.* 1997; Smith 2003). Instead, we assert that because excessive exploitation of natural resources and over-population are realities, ecologists must put massive efforts into science *for*, not *about*, a crowded planet (Palmer *et al.* 2004a). Current projections are that 8–11 billion people will live on earth by the end of this century (Lutz *et al.* 2001; Cohen 2003). Ecologists therefore have little time to waste.

What do we mean by ecological science for a crowded planet? We mean a science in which the players are actively engaged with the public and policy makers. We mean an anticipatory science of discovery that effectively informs decisions and, by so doing, moves us closer to a sustainable world – a world in which population needs are met while still maintaining the planet's life support systems (NRC 1999). Developing such a science will require a bold, proactive agenda based on four tenets. First, our future environment will consist largely of human-dominated ecosystems that are managed intentionally or inadvertently. Second, the scientific path to a more sustainable future involves some combination of conserved, restored, and invented ecosystems (Figure 1; Palmer *et al.* 2004a). Third, ecological science must be a critical component of the decision-making process that influences our planet's sustainability. Fourth, unprecedented regional and global partnerships between scientists, governments, corporations, and the public must be developed to advance the science and to ensure it is used effectively.

The desire to secure a sustainable future and to develop the supporting science is widespread (Turner *et al.* 1990; Lubchenco 1998; Levin 1999; Clark *et al.* 2001; Clark and Dickson 2003), and has been an explicit goal of the ESA for over a decade (Lubchenco *et al.* 1991). Nevertheless, what is needed to achieve sustainability remains ambiguous (Kates *et al.* 2001; Cash *et al.* 2003), and no clear plan exists for making progress. The global ecological science community must confront and embrace its responsibility and unique role in this endeavor by engaging much more actively with the public and policy makers, and by refocusing the discipline on questions that explicitly address how to sustain nature's services in the midst of burgeoning human populations.

Thus, we emphasize the need for *ecological* sustainability – that is, sustainability achieved using the breadth and depth of ecological knowledge. It is focused on meeting human needs while conserving the earth's life support systems (Figure 2). Although the problems facing humankind in the coming century will not be solved by science alone, the knowledge and collaborative approaches developed by ecological scientists can make important contributions to creating a more sustainable future.

Regional and global partnering to realize visionary frontiers

Ecology is an inherently interdisciplinary science. However, ecologists have engaged in partnerships with scientists in other disciplines, with nonscientists, and across international boundaries far less than they will need to. Such partnerships will not only move the science forward, but will ensure it informs policy decisions and public attitudes. The United States and US ecologists have a particular responsibility to initiate such partnerships, because of the nation's international political influence and wealth, its disproportionate consumption of nonrenewable natural resources, and its release of large quantities of globally transmitted pollutants (UNEP 1999).

The International Geosphere-Biosphere Programme (IGBP) has been in existence for some time and plays an important role in bringing together scientists from diverse disciplines and countries to address environmental problems that are global in scale or require a global research approach. Several current international efforts are based on similar partnerships, and should be supported and expanded. One example is the Millennium Ecosystem Assessment (MA), a program launched by the UN Secretary-General Kofi Annan in June 2001, focused on providing scientific information on ecosystem change to decision makers and the public (MA 2003). Another example is the Resilience Alliance (2004), an international program promoting theory and solutions for managing social–ecological systems.

There is a pressing need for further collaborations between ecologists and corporations, governmental agencies, and advocacy groups, at local and international levels. Business practices have substantial impacts on the environment, but if informed by ecological knowledge,

Courtesy of T Bakker, Dune Water Works of South Holland

Figure 1. *Artificial lakes covering coastal dunes represent ecologically designed systems to provide drinking water for large cities in the Netherlands.*

Courtesy of M Curtis, Montgomery County Department of Environmental Protection

Figure 2. *Students and community leaders help plant seedlings to vegetate a rain garden in Kensington, Maryland. Rain gardens such as these are designed to increase infiltration of rainwater into the soil and minimize run-off of nutrient or pollutant-rich water into stormwater systems that feed streams and rivers.*

these practices can help sustain ecosystem services, for example through appropriate waste-disposal practices or the use of less environmentally persistent chemicals (Loucks *et al.* 1999). A recent report by the Council for Environmentally Responsible Economies (CERES), a coalition of environmental, investor, and advocacy groups, examined how 20 of the world's biggest emitters of greenhouse gases are factoring climate change risks and opportunities into their business practices (Cogan 2003). The report features a checklist of specific actions that companies can take to address climate change. Ecologists can play an active role in such projects through direct involvement or through research motivated by the needs of such ventures.

Partnerships with government agencies are equally important. Agencies involved in natural resource management and environmental regulation have the legal authority, the need for scientific information, and often the resources, to implement new science programs. For example, in implementing the Endangered Species Act, US agencies identify specific ecological information requirements and, in the process, effectively frame gaps in current knowledge (Levy 2003). Multinational endeavours such as the Pan-European Biological and Landscape Diversity Program represent innovative partnerships between governmental and non-governmental groups that also depend on science, policy, and economics to protect biodiversity. The time is ripe for these programs to include more science and greater participation by the scientific community.

Ecologists need to think of themselves as entrepreneurs in a shifting, pressure-driven marketplace, where strategic collaborations and rapid responses are key to having science successfully inform policy and management. Our best chance is to have a diverse, flexible, and broadly inclusive approach that involves actively recruiting new partners and changing our own culture to best foster the new innovations required. We are, in effect, a company facing enormous challenges that, if met, will have immeasurable rewards. Like any successful company, we must be willing to change our approach and structure rapidly, to keep pace with the demands of today and the future.

An action plan

With this spirit of partnership in mind, as well as an eagerness to accelerate the development of ecological science for a crowded planet, we identify goals and associated priority actions in three areas (see the following sections). If implemented or accelerated, these actions will result in a future ecology that furthers our understanding of natural, restored, and invented ecosystems through a diverse portfolio of new ideas, partnerships, and methods. This heightened ecological understanding, and the improved communication beyond the discipline, will enable ecologists to play a pivotal role in all levels of decision making that affects the sustainability of the biosphere.

1. Informing decisions with ecological knowledge

Ecologists and ecological knowledge currently play marginal roles in many of the decisions that affect the environment. This applies equally to the daily choices individual citizens make about how they use resources and the way they perceive the actions of agencies entrusted with environmental stewardship as they make decisions about land and natural resources, ecological restoration, technology development, and the regulation of environmental hazards. In view of the growing evidence showing that better environmental decisions result when choices are informed by dialogue among scientists, policy makers, decision makers, and the public (Parsons 2001; Worcester 2002), the lack of engagement of ecologists is disturbing.

Over 5 years ago, Bazzaz and other eminent ecologists (1998) argued that the "human predicament" required that all scientists become engaged. When they began their careers, "good science consisted of two basic activities: (1) doing first-rate research and (2) publishing it in the technical literature for the benefit of scientific colleagues". They firmly believed that a third activity needed to be added by all scientists, namely informing the general public (and especially taxpayers) of the relevance and importance of ecology. While ecologists need to be more proactive in conveying their knowledge, they also need to listen and respond to the needs of society. Ecological science does not always answer the questions that matter to user groups, because user needs are not always well understood, or are not given sufficient consideration when priorities are set by the research community. As a consequence, ecology is not always seen as relevant (Cash *et al.* 2003), and ecologists are therefore not always included in contexts where they could make fundamental contributions.

This situation can be changed, but it will require new ways of identifying scientific priorities and of communicating ecological knowledge, both within our own countries and across international borders. It is no longer enough to just do the science; knowledge must be conveyed in a way that allows policy makers and the public to translate the science into action (Cash *et al.* 2003). This will require more than just effective communication. It will necessitate action plans (Panel 1), including a full-scale public information campaign centered on increasing awareness about ecological sustainability and how sustainability issues will affect the quality of people's lives, both now and in the future. In addition, a long-term, full-scale public education program is essential to ensure lasting changes in public understanding about ecology. Education will be critically important if future generations are to have the necessary knowledge, attitudes, and skills to make decisions that take ecological knowledge into account. Ecology education requires improved understanding of ecological sustainability among teachers, and the integration of ecological sustainability into the standards, curricula, or program of studies mandated by countries, states, and provinces (Berkowitz 1997; Slingsby and Barker 1998).

2. Advancing innovative and anticipatory ecological research

Generating and sharing new knowledge are fundamental to developing solutions that will underpin the sustainability of the biosphere. Ecological research questions now range from increasingly sophisticated molecular-level analyses of both living and non-living components of the world's ecosystems to integrated views of the entire globe (eg Thompson *et al.* 2001). Despite this, ecological understanding still often lags behind the scale and pace of changes to the planet (Vitousek 1994; Lubchenco 1998; NRC 2001). Anticipatory and novel conceptual, analytical, and interdisciplinary frameworks must be developed to address the complex interactions expected to influence ecological function at all scales, including the influences and feedbacks of humans on ecological processes.

The development of such frameworks requires a suite of research-related resources – infrastructure, products, and services – that will greatly enhance the design and conduct of new research, the analysis of multifaceted data, and the interpretation of complex ecological information to the public. The resources would be directed at improving access to state-of-the-art methods, including environmental sensor research and design, experimental design, quantitative analysis, measurement, interdisciplinary science, and information management and outreach (Figure 3).

To accomplish this we recommend an initiative to advance ecological research for sustainability that would involve thoughtful coordination of new programs, new centers (Panel 2), and an existing center to: (1) improve access to the latest and best expertise and tools for integrative ecological research; (2) support and promote proposed national networks of ecologically related observatories (eg National Ecological Observatory Network [NEON], Consortium of Universities for the Advancement of Hydrologic Science, Inc [CUAHSI]), coupled with the development of an international network of regional observatories which, together, would provide the necessary research infrastructure to address key ecological challenges; (3) expand collaborations and advance ecological informatics through increased support of the National Science Foundation's National Center for

Panel 1. Priority actions to increase the extent to which ecological knowledge informs decisions that influence global sustainability

Establish an international network of centers for the implementation of ecological solutions to foster partnerships between researchers, managers, and decision makers and to actively develop and communicate relevant new information to appropriate science and user groups. The centers would address policy and management issues at local to international scales by engaging interdisciplinary groups of scientists and managers in shared problem-solving ventures. Methods would range from symposia, workshops, and targeted analytical projects to strategic communication through web-based media and publications.

Develop formal rapid response teams in major political city centers worldwide (eg Washington, London, Moscow, Beijing) that draw on the expertise of ecologists to score legislative, executive, and other governmental proposals for their impact on ecological sustainability. The teams should also identify scientists to provide input and testimony on pending legislation or regulations.

Increase the number of ecologists positioned within government agencies worldwide who make decisions, or influence the decisions of others, related to global and regional ecological sustainability.

Develop and implement a major public information campaign through Internet, television, radio, and print media, to increase awareness of how global ecological sustainability issues affect the quality of people's lives and that of future generations. The campaign must be of sufficient scope and breadth that it reaches most segments of society.

Establish internationally coordinated education programs in K–12 and undergraduate ecology education to integrate contemporary concepts and advances in sustainability science and to improve teaching and learning strategies based on the best education research. Actions should focus on enhancing professional development for ecology educators, assisting with development of curriculum standards and textbooks, enhancing diversity of ecology educators, and participating in education research.

Work with diverse public, nonprofit, and religious organizations to better integrate ecological knowledge into their relevant outreach and public education campaigns.

Courtesy of SL Collins, University of New Mexico

Figure 3. *Ecologists are beginning to take advantage of emerging technologies for the remote collection of environmental information. Here one of a network of Sensor Web pods, developed at NASA/JPL, is shown monitoring the microclimate beneath a creosote bush at the Sevilleta Long Term Ecological Research site. Each Sensor Web pod contains six environmental sensors (light, air temperature, humidity, soil temperature and soil moisture at two depths) and wirelessly communicates sensor data to other pods in its local neighborhood, thus distributing information throughout the instrument as a whole. Information is then relayed via a "mother pod" to a laptop and then posted directly on the Internet (http://sev.lternet.edu/research/SWEETS/index.html).*

Ecological Analysis and Synthesis (NCEAS); and (4) improve integration of ecological knowledge into policy and management through the creation of an international network of centers for the ecological implementation of solutions. Ideally, the four components of this initiative would be international in research scope and participation. Such a combination of programs and centers would provide opportunities and services to users pursuing investigator-initiated, question-driven studies and applications (Figure 4).

In addition, other actions are needed to advance ecological research (Panel 2). New incentives to recognize and encourage research innovations are critical. Incentives and recognition are powerful motivators in science, and ecology is no exception. To encourage ecologists to devote creative energy and invest a substantial amount of time in research, reward systems must be in place and new incentives developed, particularly regarding communication to enhance sustainability.

Finally, to advance anticipatory and innovative research for sustainability requires advances in our ability to standardize, assemble, document, and share data. Ecological analyses and management decisions are commonly based on very diverse data, yet much of this environmental information has been accumulated and stored in inaccessible forms. Few tools exist that can acquire and characterize data and models and then make them globally accessible in a convenient, integrated way. A revolution in information technology that will facilitate the representation of knowledge is already beginning (eg Atkins 2003) and is essential for progress in ecological science. Through improved generic data input, access, and analysis tools, standardized metadata, and open access to environmental data, more comprehensive analysis and synthesis of ecological knowledge will be possible. Fields as varied as space science, telecommunications, and the financial markets are already reaping the benefits of rapid progress in information management; ecology must make similar strides.

3. Stimulate cultural changes for a forward-looking, international ecology

Already there is a strong research emphasis on interdisciplinary work and synthetic approaches (eg NSF 2003). However, the increasing ability of the ecological sciences to deliver the knowledge that will help society understand and address environmental problems will require substantial changes in how we do business. The future culture of ecology will need to encompass new ways of working, expanded reward systems, more diverse interactions with other disciplines, and new partners, nationally and internationally. We must foster the recognition that ecological researchers, managers, and practitioners are equal partners, as well as encouraging the development of broader metrics for eval-

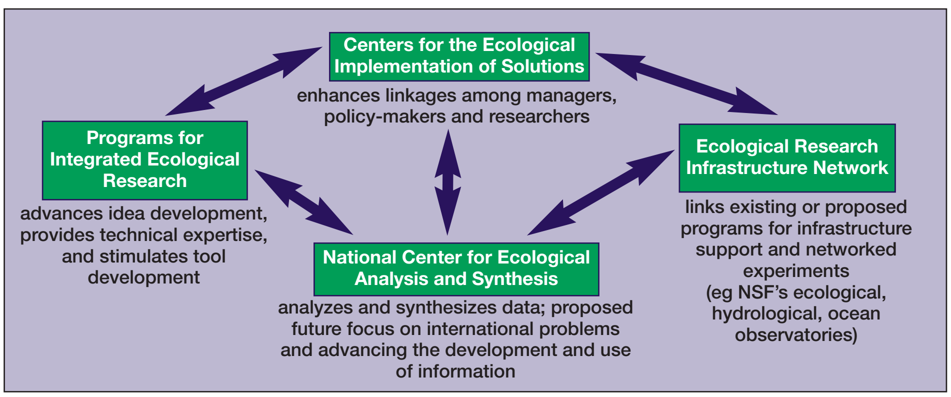

Figure 4. *Schematic of the four components needed to advance research for ecological sustainability. Where appropriate, a research project could benefit from all four or could enter or leave the sequence at any point, depending on needs. This structure creates a highly flexible set of resources (infrastructure, products, services) for the full spectrum of research and implementation needs (see Palmer* et al. *2004b).*

uating scientists both within and outside of the academy. To achieve this cultural growth will require a greater understanding of what promotes successful collaboration, an increasingly diverse research community, and a concerted effort to internationalize our work and access to it.

In the future, we will face an escalating need to seek and amalgamate relevant expertise to address emerging or anticipated environmental problems. Teams will be built rapidly and will often include members who have not collaborated with each other in the past. These teams will need to provide solutions, or at least scientifically well-informed choices, within short timeframes. While there is already a general acceptance that collaboration is critical to ecological science, very little work has been done to examine how and where interdisciplinary collaborations come about, and when and why they lead (or not) to scientific innovation (Rhoten 2003). Indeed, social scientists have determined that ecology is not "collaboration ready", either in terms of its technical infrastructure or its social environment (Olson and Olson 2000). Tools and skills for collaboration may be as important as technological infrastructure for scientific progress. We need to understand what promotes successful collaborative enterprises and to communicate that knowledge within our research communities. This will require progressive training of current ecologists by creating opportunities for young ecologists to interact and by actively recruiting a greater diversity of skilled people to the study of ecology.

Our collaborations must extend well beyond national boundaries. After all, environmental problems and sustainability are international and multidisciplinary issues. The shift towards internationalization is already occurring, at least within the ESA; 16% of members live outside the US and 80 countries are represented within the membership (ESA 2003). However, we need to go much further to create international partnerships among researchers, managers, practitioners, and businesses. For example, the European Union for Coastal Conservation (EUCC) is an association with members and member organizations in 40 countries; it was founded in 1989 with the aim of promoting coastal conservation by bridging the gap between scientists, environmentalists, site managers, planners, and policymakers. Currently, it is the largest network of coastal practitioners and experts in Europe. The activities coordinated by the EUCC promote coastal conservation while integrating biodiversity concerns with coastal development, by mobilizing experts and stakeholders, providing advice and information, and implementing projects.

The scale of ecological science must match the scale of the most pressing challenges to ecological sustainability, including climate change, invasive species, depleted fisheries, and water and land-use changes (eg NRC 1999). Much of the field of ecology, however, continues to focus on local scales and relatively short time scales. Furthermore, the predominantly national focus of many professional societies and institutions reinforces an insularity that impedes progress on regional and international scientific problems. Broadening the discipline requires a more proactive approach to promoting international cooperation, activities, and collaborations among ecological and environmental scientists. There is a need for a multinational science agenda to exchange knowledge and build collaborative multinational projects in areas that are critical for ecological sustainability. This agenda would ensure that access to ecological knowledge is not impeded by language barriers, infrastructure, or training.

Panel 2. Priority actions to advance innovative and anticipatory research that contributes to ecological sustainability

Fully scope and obtain funding for a four-pronged initiative to advance ecological research for sustainability. This initiative requires close coordination between two novel programs, an existing center (the National Center for Ecological Analysis and Synthesis – NCEAS), and new centers (Figure 4). The goal of the initiative is to facilitate research project development (programs for integrated research), large-scale experiments and data collection (infrastructure networks), synthesis (NCEAS), and, the linkage of science to solutions (centers for implementation of solutions).

Establish awards for research breakthroughs, new instruments, and new technologies that would catalyze advances in ecological science; this should also advance interactions between ecologists and other disciplines.

Establish an international contest among collaborative groups to solve an annual ecological challenge that centers on fundamental research for sustainability, restoration, or invented ecological solutions. These challenges might require the development of new technologies, analytical approaches, models, and experimental designs.

Vastly and rapidly enhance the availability of data by creating an international ecological data registry that provides a freely searchable data catalog that identifies data sets and their owners. This initiative would be accomplished by encouraging ecological journals to require that raw data and metadata be made freely available to others and encouraging government and NGO groups to do likewise; and by providing training in ecoinformatics as a core curriculum option for ecologists.

Concluding comments: activating a research community

It will be no small task to move ecologists from their historical focus on pristine systems towards actions to ensure that ecological science makes a difference in the world's future. A focus on ecological sustainability does not mean advocacy. Instead, it means a shift in the priorities of basic and applied research to concentrate on sustaining ecosystems and large human populations. It also means that ecologists must strengthen their role of providing ecological knowledge that is needed to inform decisions. Effective communication with public and private sector decision-makers and resource managers will be essential in anticipating emerging research needs and drawing on ecological knowledge to solve environmental problems. Given the accelerating pace of global population growth, of natural resource exploitation and degradation, and of environmental contamination, we have little time to waste. The future depends on ecologists being not only

Panel 3. Priority actions to stimulate cultural change for a forward-looking, international ecology

Globalize access to ecological knowledge by promoting efforts by international groups to develop an International Federation of Ecological Societies. Efforts should include activities to foster collaborations, formal mechanisms for the translation of key articles from prominent foreign-language ecology journals and other sources into English, and vice versa.

Promote an international agenda for global ecological science by holding thematic meetings that highlight international and interdisciplinary needs for ecological science coming out of forums such as the Convention on Biological Diversity and the Intergovernmental Panel on Climate Change. These meetings should focus on sustainability science.

Bolster an international young ecologists' research community by developing an international ecological scholars program similar in nature to the Rhodes and Gates Scholars programs, and by creating programs for exchange of students and postdoctoral researchers to research labs and meetings. We specifically advocate an annual international graduate student conference, to be held once a year, and comprised of attendees from both developing and developed nations (with at least half of the participants being non-US citizens).

Establish programs for training in collaboration that bring together ecologists with extensive collaborative experience and social scientist partners to develop and implement training in the art of successful partnership; develop web-based education materials (eg primers for successful collaboration).

Stimulate proactive changes in flagship ecological journals and in meeting symposia to reflect the increased emphasis on interdisciplinary, solution-driven science, particularly where this is focused on regional and global scale problems of interest to both ecological researchers and practitioners.

Convene a meeting of key leaders in research, management, and business to reconsider the reward system for novel scientific collaborations and to precipitate National or Royal Academy-level studies to identify a plan for stimulating changes in the reward systems.

Promote ethnic and gender diversity and equality in the ecological sciences by forming partnerships with sister societies in other countries and developing or enhancing programs to recruit under-represented groups.

stellar researchers but also becoming purveyors of knowledge that actively informs decisions. We can no longer simply wait for our collective knowledge to be discovered by those who do not even know they need it.

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