Linking knowledge to action: the role of boundary spanners in translating ecology

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One of the most effective ways to foster the co-production of ecological knowledge by producers and users, as well as encouraging dialogue between them, is to cultivate individuals or organizations working at and managing the boundary between the two groups. Such "boundary spanners" are critical to ensuring scientific salience, credibility, and legitimacy, yet they remain relatively underused in ecology. We summarize some of the major roles of boundary spanners in translational ecology, and suggest that effectiveness in translating ecological information depends on several key factors. These include organizational and individual commitment to boundary spanning over the long term; development of useful, co-produced products and tools that can subsequently assume boundary-spanning roles of their own; dual-accountability frameworks that involve both science providers and users; and identification, training, and retention of science translators who possess a suite of professional skills and individual traits that are rare in scientific circles.

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Communication between science and society has never been more vital than it is today. Modern environmental problems (eg climate change, pollution, environmental justice, non-native invasive species, extinction) are characterized by complexity, uncertainty, large temporal and spatial scales, and irreversibility, and will require innovative, participatory, and multiparty approaches to solve them (Burns *et al*. 2003; Bucchi and Trench 2008; Bixler *et al*. [2016] and accompanying papers). Translational ecology (TE) has a central role to play in tackling emerging environmental problems by facilitating (1) the dissemination of science to society, (2) the serious consideration of science by decision makers, (3) the promotion of dialogue with stakeholders, and (4) the acquisition of information essential to innovation. However, the infrastructure and business practices required to fulfill these important roles remain underdeveloped in ecology. A key question is how individuals or organizations involved in the production or use of ecological information can be organized and positioned to take advantage of new science, management practices, partnerships, and ways of thinking generated from outside their own organization or discipline.

Boundary spanners are institutions, groups, or individuals that straddle the divide between information producers and users (eg scientists and non-scientists, respectively), produce boundary products or tools ("boundary objects") that enable communication between these two groups, and are accountable in some fashion to both groups (Tushman 1977; Guston 1999, 2001; Parker and Crona 2012). Boundary spanners can have research-focused roles (where external relationships are primarily with universities, research institutions, etc) or technical-service-focused roles (where external relationships are primarily with customers), but in general their two central functions relate to information acquisition and delivery (Aldrich and Herker 1977; Ernst and Chrobot-Mason 2012). In this paper, we draw from our own experiences and those of the organizations we work with to make the case that more formal adoption of boundary-spanning principles and practices by entities that produce ecological knowledge would go far toward solving some of today's persistent environmental problems.

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Boundary-spanner roles

Boundary spanners endeavor to achieve an appropriate balance of salience (relevance of the science to users' needs), credibility (the perceived reliability and adequacy of the science employed), and legitimacy of information (the perception that the production process has been respectful of stakeholders' values and beliefs) through three main functions: communication, translation, and mediation (Cash *et al*. 2003, 2006). Communication is a two-way learning and teaching process that is active, ongoing, and inclusive. Cash *et al*. (2006) divided this procedure into "convening" and "collaboration" functions. The former (bringing relevant parties into direct contact) provides the foundation for collaboration, translation, and mediation that may come later (Figure 1), whereas the latter refers to the communication task of bringing actors (experts, decision makers, other stakeholders) together to co-produce applied knowledge or tools. Actors must be able to understand one another but different experiences and assumptions, and even language barriers, often hinder mutual comprehension, requiring boundary spanners to play a translational role as well (Figure 2). Trade-offs between salience, credibility, and legitimacy are unavoidable (Cook *et al.* 2013), and some level of mediation is usually necessary to arrive at a balance that is amenable to the majority of stakeholders. Mediation is especially critical to the legitimacy of the boundary-spanning process, as it increases transparency, forces stakeholder perspectives to come to the surface, and provides a safe arena for discussion and negotiation (Cash *et al.* 2003; Kocher *et al.* 2012). Not all boundary spanners carry out all of these functions in equal measure, and in many cases mediation in particular is best carried out by specially trained individuals or units.

Characteristics of effective boundary spanning in ecology

Ultimately, effectiveness in translating ecological information depends on (1) commitment to a well-planned system for boundary-spanning activities; (2) development of useful products by the boundary-spanning unit and its partners; (3) the existence of an accountability framework that includes both science providers and users; and (4) the traits of individual boundary spanners (Guston 2001; Cash *et al.* 2003, 2006; Roux *et al.* 2006). Below, we discuss these characteristics and provide some real-world examples (see WebTable 1 for background information on boundary-spanning organizations referred to in this paper).

Boundary-spanning organization and structure

Boundary-spanning roles or entities are increasingly found within organizations that recognize the importance of external relations and the value of external information (Ernst and Chrobot-Mason 2012). These organizations are effective in translating technical information for customers, and incorporating external information and innovations into their own business practices (Tushman 1977; Cash *et al.* 2003). In ecology and the environmental sciences, past examples of successful boundary spanning have been scarce but are becoming more common (see examples below and WebTable 1). One issue is that organizations in these fields – often under some level of financial duress – have a tendency to commit to and then discontinue boundary-spanning activities in response to the ebb and flow of political and funding cycles, a pattern that is partly to blame for many of the failures in TE over the past three decades (eg Peters 1991; Schlesinger 2010; Harris 2012).

Effective boundary-spanning units can range in size from a single individual to an entire government agency or non-governmental organization (NGO; see examples below and WebTable 1). Organizations that work in highly uncertain, complex, or ill-defined settings require greater levels of extra-organizational communication,

Figure 1. *Legitimacy among most science-user communities is developed over time and through repeated two-way interactions. Some sort of "peripheral membership" in the user groups is often key to successful boundary spanning. Here, a group of forest and fire managers, private stakeholders, students, academic and agency scientists, and boundary spanners from the US Forest Service, University of California Cooperative Extension, and a number of non-governmental organizations discuss the impacts of climate change on ecosystem management in a national forest in the southwestern US. Many members of the group are acquainted, and there are multiple networks of strong professional and personal relationships represented within the group.*

and investment in boundary-spanning activities should be high. Probably the most important organizational characteristic is a long-term institutional commitment to the importance of the boundary-spanner role (Lemos *et al.* 2014), and recognition of the special skills required for and stresses experienced in that role.

The credibility and legitimacy of the boundary-spanning unit is one of the foundational keys to success. The unit and its employees must be perceived to be experts in – or at least highly familiar with – the issue at hand ("competence credibility"), which is a function of accomplishments, originality, relevance, technical knowledge, and ability to communicate (Roux *et al.* 2006). At the same time, the manager/client must be comfortable with the presence of the boundary spanner and trust in the legitimacy of the individual, group, or institution (sometimes called "safety credibility"), which is influenced by similarities in education, technical capacity, cultural background, work philosophy, and even recreational activities (Roux *et al.* 2006). Legitimacy is often overlooked by scientists but can have an important influence over the perceived salience of science to users. When organizations hire and train individual boundary spanners, they need to understand the importance of both these sources of credibility.

Effective boundary-spanning units, or "boundary units", are dynamic and nimble, capable of responding to the changing interests of actors on both sides of the boundary, and able to inform and transform the practices of all involved parties (Cash 2001; Levina and Vaast 2005;

Figure 2. An ad hoc boundary-spanning organization composed of representatives from federal agencies (US Forest Service, US Geological Survey) and universities (University of California–Davis and Michigan State University) conducts a workshop for resource managers and key stakeholders in a southern California town to collect information on the ecological values of chaparral-dominated watersheds, and to describe a series of tools in development that will assess ecosystem services provided by such watersheds under different future climate, management, and wildfire scenarios.

McNie 2007). Effective boundary units and their organizations provide an institutionalized space in which long-term relationships between the unit and its partners/clients can grow and evolve (Cash 2001, and see next section). Successful boundary spanners are best retained by organizations that provide supportive, rewarding, and flexible environments with sufficient levels of autonomy, variety, institutional feedback, and employee participation in important job decisions (Singh 1998). Both experience and social capital take time to accrue, and longevity in a role can facilitate better boundary spanning (Wall *et al.* 2017). A true partnership implies a multiyear planning cycle, which means that turnover of individuals in key boundary-spanning positions over the course of that time period can set partnerships back considerably, as it takes time to rebuild partnerships (Lubell *et al.* 2014). Organizations engaged in TE should establish reward and promotion systems that acknowledge the unique nature of boundary-spanning work, which combines skills and characteristics of scientists, managers, and end users.

Examples of boundary-spanning organizations

Federal: US Forest Service Region 5 Regional Ecology Program

Two regions of the US Forest Service (USFS; Region 5: California, Hawaii, Pacific territories; Region 6: Oregon, Washington) support boundary-spanning organizations of ecologists, with ecological scientists based within the USFS management arm. These organizations embody both the boundary-spanning and "embedded researcher" frameworks proposed by Cook *et al.* (2013) and are among the groups who are best positioned to facilitate science delivery to management. In Region 5, the Regional Ecology Program (REP) consists of a total of 12 staff members, two of whom are based at the Regional Office (RO) and the remaining ten are divided into groups of two in each of five "provinces" of three to four national forests. Employees of the REP are supervised on the national forests where they work but their work supports all USFS units in the province, and annual programs of work and funding sources are negotiated with representatives from all served units and the RO. Approximately 75% of REP funding comes from the RO, with the remaining 25% either negotiated with the national forests being served to support involvement in high-profile projects, or obtained through grants, agreements, and cost-sharing arrangements with agencies, universities, foundations, and other funding organizations. Although the primary aim of the REP is to deliver up-to-date and credible ecological science to USFS managers in support of planning and project implementation, it also plays a major role in disseminating science to and interacting with managers and the general public. The REP thus inhabits multiple boundaries: between the RO and the field units, between the USFS and external stakeholders/partners, and between science producers and science users. The REP's effectiveness is a product of both competence and safety credibility (social capital). The group is composed of respected scientists who work directly within the management arm of the agency, a situation that gives them access to and familiarity with the managers they serve and work with, unlike external scientists, who have a more limited level of access and involvement.

State and county: University of California Cooperative Extension

Cooperative Extension is a nationwide system that spans boundaries between universities, farmers, and natural resource managers. The system consists of agricultural experiment stations and a Cooperative Extension Service being linked to a public university in every US state. In California, the extension is based in four University of California (UC) campuses, with 700 academics and 130 campus-based extension specialists; nine Research and Extension Centers and 200 local county-based advisors at 57 local offices throughout California complete the network. County-based advisors live and work in the communities they serve, which allows them to develop social capital for problem-solving by building long-term relationships with managers. Advisors are evaluated on a wider range of performance criteria than are campus-based researchers, including applied research and creative extension activities; examples of key performance criteria include credibility with information users, effectiveness of extension activities, networks developed, and collaborations. Advisors have a high level of autonomy to develop priorities and programs to meet local needs. Local natural-resource extension programs typically focus on working landscapes and water-quality issues, invasive species, habitat preservation, and ecosystem restoration. The UC Cooperative Extension (UCCE) is an example of a very large boundary-spanning unit with impressive resources, engagement in multiple current statewide and regional projects, and many success stories. A typical example is UCCE's development of ranch water-quality planning and training to reduce nonpoint source pollution, where extension advisors and specialists conducted 70 short courses between 1995 and 2007 that were attended by over 1000 rangeland managers in 35 counties. The content of these courses included assessment techniques, implementation practices, and monitoring approaches, and, following the training, most participants went on to develop a water-quality plan and implement protection practices. The effectiveness of the program depended greatly on the long-term participation of range advisors in the range management community, which increased trust and allowed development of boundary products that fit local needs and practices.

Non-governmental organization: Wildlife Conservation Society

Wildlife Conservation Society's (WCS's) mission is to save wildlife and wild places worldwide. To do so, WCS uses science to discover and understand the natural world. This knowledge helps them engage and inspire decision makers, communities, and millions of supporters to take action to protect the wildlife and wild places that society cares about (www.wcs.org/about-us). Achieving this "discover, inspire, and protect" theory of change requires that WCS facilitate collaboration and information flow between research, policy, and practitioner communities. It also necessitates understanding needs and interests of policy makers, non-governmental organizations (NGOs), and local communities, so that WCS's science has a clear pathway to implementation. Representatives of WCS work closely with boundary stakeholders to identify practical science needs, provide targeted scientific input, and produce science-based tools for conservation that are widely disseminated and freely available. To inspire others to help protect nature, WCS builds strong and trusting relationships with policy makers and practitioners at all levels in an effort to help them interpret science and make informed decisions about protecting and managing wildlife and habitats in ways that reflect their interests and concerns. In addition, WCS provides government agencies with additional personnel, resources, research, and expertise on specific conservation issues that require attention but fall outside the skills available in those agencies. These services help satisfy obligations to maintain wildlife for public benefit, and by providing them, WCS influences conservation policies and actions. Since the early 1900s, WCS has also supported governments and communities in creating or expanding 245 parks and protected areas around the world (www.wcs.org/our-work/protect); in the US, for example, WCS played a key role in the recent creation of Wyoming's Path of the Pronghorn, the first federally designated migration corridor in the country. The organization's approach to TE focuses on the necessity of establishing both competence and safety credibility, understanding the sociopolitical nuances of the issue at hand, and the importance of long-term engagement.

Non-profit partnership: The Longleaf Alliance

The Longleaf Alliance (LLA) was established to promote the restoration of longleaf pine (*Pinus palustris*) forests in the southeastern US. The LLA began as an extension-type organization at Auburn University in Alabama, eventually transitioning to a non-profit – 501(c)(3) – corporation. The mission of the LLA is "to ensure a sustainable future for the longleaf pine ecosystem through partnerships, landowner assistance and science-based education and outreach" (www.longleafalliance.org). The Alliance's chief focus is re-creating the culturally diverse connections to longleaf pine that have been lost as the species has declined, emphasizing economic, aesthetic, and wildlife management considerations along with biodiversity. The LLA has a full-time staff of about a dozen, and the board of directors, which sets priorities and assists in fundraising, is composed of private landowners, forestry professionals, academics, and federal agency employees. Funding derives from various sources, including memberships, donations, grants and agreements, field-course tuition, and sales. The LLA's TE efforts primarily consist of: (1) Longleaf Academies and other field workshops that provide training to a target audience of private landowners and conservation professionals; (2) biannual conferences on longleaf pine conservation and management; and (3) on-the-ground consultation for private landowners. Successful collaboration with private landowners has been the hallmark of LLA as an organization and represents effective TE in a region with diverse ownership patterns. Since 1995, LLA efforts have led to the establishment of more than a million hectares of new longleaf pine stands across the southern US.

Other organizational examples can be found in WebPanel 1.

■ Boundary products

Creating tools and products matched to the needs and capacities of both the producer and the user is a key part of boundary spanning (Panel 1; Star and Griesemer 1989). Effectual boundary products (or "boundary objects") can be understood and applied by non-scientific users, and in the case of tools, are simple enough to be used, updated, or rebuilt for future use even in the absence of the original designer(s) of the tool (Panel 1). Boundary products are not necessarily tangible and may

Panel 1. Examples of boundary products

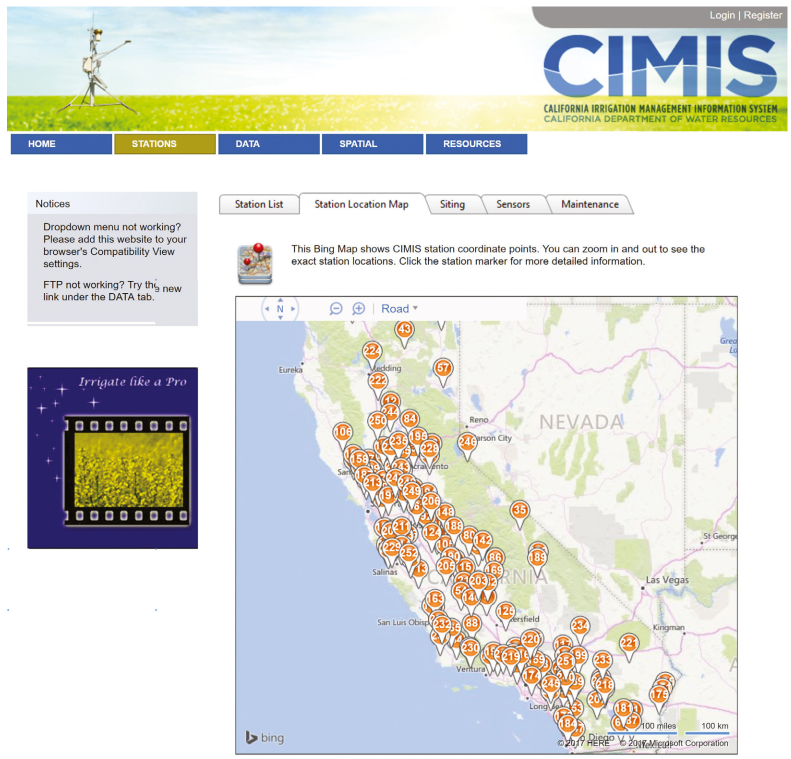

Figure 3. CIMIS webpage showing the locations of weather stations included in the system. Users match their local climate to the climate of a nearby station and then use the meteorological data obtained from the station to calculate evapotranspiration rates and irrigation needs.

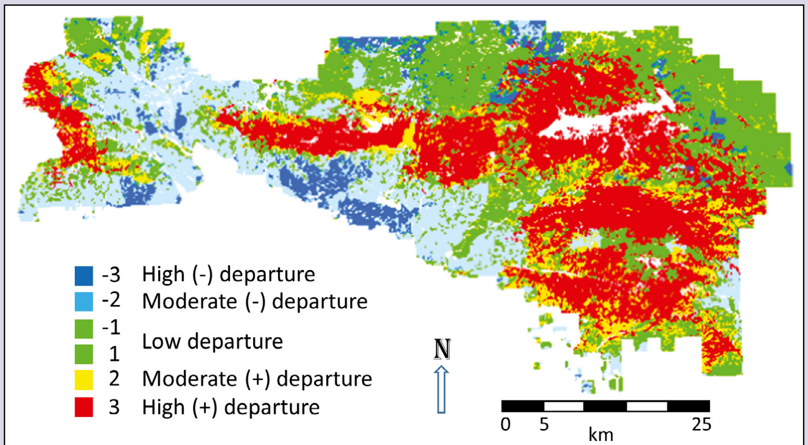

Figure 4. The 2010 Fire Return Interval Departure (FRID) map for the San Bernardino National Forest in California. Cool colors depict areas where current (since 1908) fire return intervals (FRIs) are shorter than under pre-Euroamerican settlement reference conditions; warm colors depict where current FRIs are longer than under reference conditions; areas in green are more or less within the historical range of variability (HRV) for fire frequency. This tool, which is updated annually, is available for all national forests in California, and informs fuels and fire management planning, forest planning, restoration project planning, and a variety of other environmental analyses.

The California Irrigation Management Information System

The California Irrigation Management Information System (CIMIS; www.cimis.water.ca.gov) is an integrated network of about 150 automated weather stations situated throughout California (Figure 3). Development of the CIMIS was initiated in 1982 through a joint project between the University of California (UC)–Davis, the California Department of Water Resources (CDWR), and the UC Cooperative Extension to conserve water resources in the state by improving irrigation efficiency. The CIMIS uses weather information to calculate standardized evapotranspiration (ET_o) rates of short canopy crops to make this information available to the end users; irrigators then use crop coefficient (K_c) values to convert ET_o to potential crop evapotranspiration (ET_c), which directly informs irrigation needs. Over 40,000 registered users retrieve data from the CIMIS network, including farmers, government agencies, utilities and local water districts, academics and researchers, consultants and hydrologists, and even golf course managers, among many others. Thousands more users access CIMIS data from secondary or tertiary sources. Data can be manually downloaded, automatically accessed, or delivered by email. The system is maintained by CDWR and is free to users. An evaluation completed in 2000 found that CIMIS reduces statewide agricultural water application by more than 132 million cubic meters (107,300 acre-feet) annually, and that estimated annual benefits (~\$65 million) far outweighed annual costs (~\$850,000) (Parker *et al.* 2000; Eching and Moellenberndt 2000).

California Fire Return Interval Departure (FRID) geodatabase

The California Fire Return Interval Departure (FRID) geodatabase is a boundary tool developed by the USFS Region 5 Regional Ecology Program (REP), in collaboration with The Nature Conservancy, UC Davis, USFS Region 5 Fire and Aviation Management staff, and CalFire. In fire-prone places like California, restoration and management at landscape scales require information on fire history. REP began by summarizing data on pre-Euroamerican settlement fire frequencies in important vegetation types (Van de Water and Safford 2011), then applied these data to a fusion of USFS vegetation maps and the California Fire Perimeters geodatabase. This repository extends back to the early 20th century and is updated each year by CalFire with information provided by state and federal agencies. A geospatial product was developed that provides easy access to fire history information, including contemporary departures from historical (reference)

(*continued*)

fire frequency patterns, which can help prioritize areas in need of fire, fuel, and ecosystem restoration, among other things (Figure 4; Safford and Van de Water 2014). Use of the product has highlighted missing data in the underlying fire perimeters dataset as well as errors in regional vegetation mapping, and has led to improvements in both datasets and in information about departures from reference patterns. The tool is now updated annually by the USFS Region 5 Remote Sensing Lab and is used mostly without the direct involvement of the REP.

Adaptation for Conservation Targets (ACT) framework

In 2007, WCS convened a group of conservation scientists from conservation NGOs, academic institutions, and government agencies to develop a tool to help conservation practitioners proactively plan for the effects of climate change on species and ecosystems. The resulting "Adaptation for Conservation Targets (ACT)" framework is a simple yet structured planning process that draws on familiar decision-support tools (eg structured decision making, adaptive management, Open Standards for the Practice of Conservation) and builds common elements of conservation planning (eg local knowledge, conceptual models, scenario planning) into a process tailored specifically for addressing climate change (Cross *et al.* 2012). Use of these familiar concepts is intended to facilitate ease of adoption by natural resource managers and planners without the need for specialized training. The individual steps of the ACT framework are depicted in Figure 5. Application of the framework was first carried out by the Southwest Climate Change Initiative (SWCCI; an alliance of NGOs, universities, and federal agencies) in climate-change adaptation planning efforts in the Four Corners region of the southwestern US (Cross *et al.* 2013), with natural resource managers, scientists, and conservation practitioners from local, state, tribal, and federal agencies and organizations participating in ACT workshops held in each of the four states (Utah, Colorado, New Mexico, and Arizona). Post-workshop surveys indicated that these workshops increased participants' capacity to address climate change by enhancing their understanding of potential effects and guiding the identification of solutions (Cross *et al.* 2013). Since these initial pilots, the tool has been used to accelerate climate-change adaptation planning and action in a variety of locations (eg New York, Oregon, Montana, Idaho, California, Ontario, the transboundary US–Canada Rocky Mountains, and the Great Plains LCC region) for a diversity of species and ecosystem features by a range of conservation practitioners.

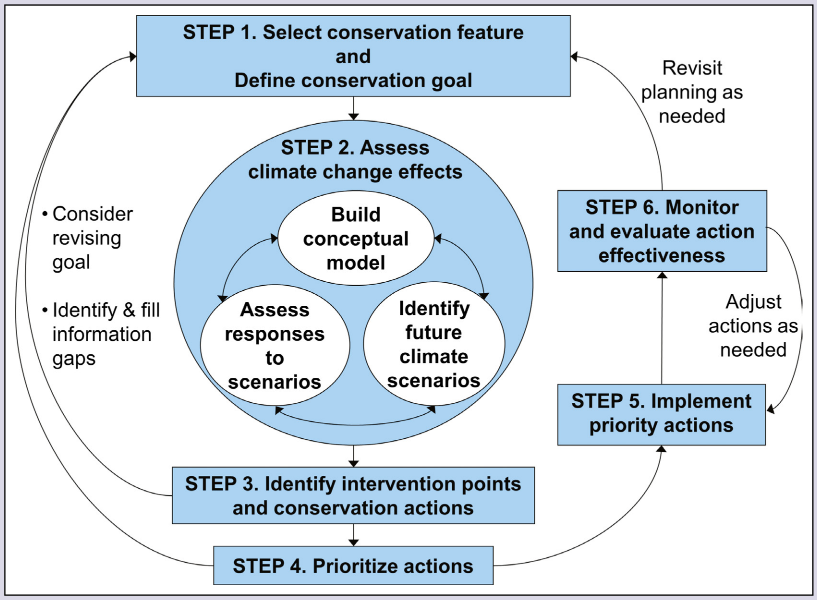

Figure 5. *The Adaptation for Conservation Targets (ACT) framework for climate-change adaptation planning.*

be represented by new processes, events, or traditions. The production of applied ecological products has customarily been unidirectional, and dominated by the creation of scientific products that are simply "unloaded at the dock" (eg published) and left for people to use, provided they can figure out how to use them (Cash *et al.* 2006). However, the creation of effective boundary products requires that relevant groups and organizations fully engage and participate in their development (co-production), and sustain that engagement over time (Joyce 2003; Roux *et al.* 2006; Meadow *et al.* 2015).

Collaborative development of products and tools between scientists and end users is more likely to produce salient information because it engages customers at an early stage in identifying and defining data and product needs. Co-production also enhances credibility by bringing multiple types of expertise into the process and enhances legitimacy by offering stakeholders greater access to the knowledge-production process (Cash *et al.* 2003; Nel *et al.* 2016). Although such products and tools may require an experienced boundary spanner to successfully develop, market, and employ them, under the right circumstances tools and other products can assume a boundary-spanning role of their own if users adopt them (Panel 1). Long-term use and ownership are more likely to occur when ongoing relationships, strong multi-way communication, and focus on the production of useable science are maintained (Meadow *et al.* 2015).

Shared accountability

Ideally, boundary spanners will have defined responsibilities and accountability to both knowledge-producer and -user communities (Panel 2). Such shared accountability arrangements oblige boundary spanners to address the interests, concerns, and perspectives of actors on all sides of the boundary (Guston 2001; Cash *et al.* 2003). Although boundary spanners are usually core members of only one of the communities in any given activity, some level of shared accountability ensures that boundary negotiation is a balanced and dynamic process, and represents the needs and cultures of both parties as they evolve. Lave and Wenger (1991) suggested that effective boundary spanning requires what they call "legitimate

Panel 2. Examples of dual accountability

USFS Region 5 Ecology Program (REP)

The Region 5 REP (see main text) is a Regional Program, but funding is shared with the national forests in Region 5. The REP is managed and coordinated from the Regional Office, but direct, formal supervision for each field position ("Province Ecologists" and "Associate Province Ecologists") is carried out by the hosting National Forest. Both regional and local inputs are included in annual performance reviews. Annual program-of-work meetings are held at the beginning of each year, with participation by Regional Office staff, local supervisors, and other interested local staff, along with resource staff officers from each of the units being served (each Province Ecologist serves 3–4 national forests). A regional annual report and accomplishment highlights are published each year, which serve to secure annual regional funding, while ongoing support and interaction, local accomplishment reporting, and annual meetings with leadership teams from each served field unit assist in securing local support.

University of California Cooperative Extension (UCCE)

Like other US Cooperative Extension programs, funding for UCCE (see main text) is cooperative, meaning it derives from a mix of federal (USDA), state (the Land Grant University, in this case UC) and local sources. Funds from the USDA are allocated to a variety of programs and purposes, while the state, via the participating university, underwrites academic employee salaries and provides funding for statewide program operation; county governments provide base funding for local UCCE offices and operations. UC Extension agents based in California counties and local UCCE support staff report annually to local boards of supervisors on their activities. These meetings are also used to provide input on the preferences of counties and other local stakeholders/partners in terms of local programs and science support. Surveys of user satisfaction and learning are conducted throughout the life of a program or project and used to assess effectiveness. County advisors are evaluated on both academic criteria, including applied research and professional competence, and the quality and volume of their extension program. Input is solicited from both academic colleagues and local clientele when deciding on tenure and promotions.

US Fire Science Exchange Network

The US Fire Science Exchange Network was developed by the Joint Fire Sciences Program (JFSP), a science production and delivery partnership of the US Department of Interior and the USDA (see WebTable 1). The network includes 15 independently operating regional exchanges (eg California, the Great Plains, the North Atlantic). Each regional exchange receives base funding from JFSP, but the exchange charters require regional buy-in (funding, in-kind contributions, and so forth) from participating agencies and organizations; universities hosting some of the exchanges also provide in-kind support. Regional advisory boards are composed of representatives of fire science user groups (eg federal and state agencies, local and county fire departments, cooperative extension agents, NGOs, private landholder groups), who provide program oversight, evaluate exchange practices, and collect and relay information from stakeholders. The exchanges participate in an annual national evaluation report and submit refunding proposals to JFSP every 3 years. Most exchanges conduct user surveys following each sponsored event, and some are organized into subregional exchanges that allow for closer interaction with the science producer and user groups.

peripheral participation", wherein boundary spanners are "legitimate members" of both of the served communities while still remaining peripheral to them, as full participation on either side usually impedes effective boundary spanning. By recommending legitimate membership, Lave and Wenger (1991) meant that both communities recognize, value, and trust the boundary spanners (who participate in both communities); that is, they have access to the communities' practices, languages, and tools. Where shared accountability and understanding exist, boundary spanners will be more likely to succeed in the critical communication, translation, and mediation functions described above, which are especially difficult when groups are divided by language barriers, experiences, and assumptions.

Individual traits of successful boundary spanners

Being directly involved in the creation and application of scientific knowledge to critical environmental problems is important and exciting work, but successful individuals must possess a suite of traits that allow them to achieve the proper balance of salience, credibility, and legitimacy in their efforts (McNie 2007; Bednarek *et al.* 2015). Here, we explore several attributes – including breadth, depth, social learning, and perseverance – common to effective TE boundary spanners (see also Schwartz *et al.* 2017). For a boundary spanner, individual credibility is necessary but insufficient. To achieve legitimacy and salience, boundary spanners must also be client-driven; innovative, creative, and collaborative; inclusive and tolerant of different ideas and perspectives; and excellent communicators (Kocher *et al.* 2012).

It is important that boundary spanners be sufficiently educated and/or experienced within a discipline to warrant respect from both sides of the boundary they serve. However, effective boundary spanners are also generalists and jacks-of-all-trades – scientist, manager, mediator, diplomat, and so on – as well as peripheral members of various and often-times competing communities. Effective boundary spanners recognize that knowledge homogeneity (learning only within and not across groups) is an obstacle (Roux *et al.* 2006), whereas knowledge diversity is beneficial.

The legitimacy of effective boundary spanners in ecology is based upon social learning, teamwork, and the building of trust. Social skills are crucial to successful TE (Wall *et al.* 2017). Efficient knowledge transfer between humans happens when people are familiar with one another and understand something about each other's background, experiences, and perspectives (Roux *et al.* 2006; Kocher *et al.* 2012; Meadow *et al.* 2015). Scientists and information end users are often too busy and/or too disconnected from one another to interact successfully, and boundary spanners must figure out ways to bridge this gap, often through social or informal learning opportunities (WebFigure 1). Overcoming the science–society divide requires the ability and inclination to work with a range of different partners, and to incentivize change in their organizations and practices. Although the ability to work with different parties is shaped by institutional support and formal roles, the individual's skills, experiences, and informal roles ultimately drive success. A boundary spanner's ability to acquire, assimilate, and exploit external information is strongly related to the depth of their experience and the social capital they have with stakeholders (DeBrulle *et al.* 2014).

Boundary spanners must have the patience to persist through the often inefficient social learning environments in which they work. Boundary-spanner roles can be highly stressful, and burnout is common. Stressors include role conflicts (expectations/demands of the employer are incompatible with those of the customer or different partners), role ambiguities (information needed to adequately perform the role is lacking, and employers and customers have different expectations), and role overload (cumulative demands exceed the boundary spanner's abilities and motivation; Singh 1998). Boundary spanners must be resilient, dedicated, thick skinned, and levelheaded (Berger and Cain 2014), and they require excellent task- and time-management skills. Because boundary spanners work within porous boundaries, their positions can become unstable, and they are often pulled in different directions by different stakeholders (Parker and Crona 2012). For example, strong boundary-spanner connectedness to science production enables innovation, but it can exert a gravitational pull away from the more difficult and less honored role of stakeholder interaction (Liu and Stuart 2010; Jandhyala and Phene 2015).

Conclusions

In 2009, the Joint Fire Science Program, a federal interagency fire science research and applications partnership, commissioned a study to investigate the dissemination and use of fire science information by US fire and resource managers (Kocher *et al.* 2012). Managers responded that they did not need more scientific information but rather that they had *too much* information, and desperately needed help in screening and evaluating the science, and with applying the information to problems on the ground. The lesson here is not that new science is unnecessary but rather that better mechanisms for translating and conveying existing science are needed, and that interactions with the managers who use the science must be expanded.

The growing recognition that environmental-management problems cannot be solved simply by generating more science is leading to an increased focus on how organizations and researchers translate ecological science to society. By inhabiting the boundary between science and application, translational ecologists are uniquely positioned to wrestle with the scale, uncertainty, risk, and entrenched interests that make many current environmental problems seem intractable (Balint *et al.* 2011). Boundary spanning is a key tool in the TE toolbox, and a commitment to increasing the social value, relevance, and application of the ecological sciences will require an expanded investment in boundary-spanning training (Schwartz *et al.* 2017), employment, and organizations.

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