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OPINION ARTICLE

Primed for Change: Developing Ecological Restoration for the 21st Century

Nancy Shackelford,[1,2] Richard J. Hobbs,[1] Joanna M. Burgar,[3] Todd E. Erickson,[1,4] Joseph B. Fontaine,[5] Etienne Laliberté,[1] Cristina E. Ramalho,[1] Michael P. Perring,[1] and Rachel J. Standish[1]

Abstract

Restoration is a young and swiftly developing field. It has been almost a decade since the inception of one of the field's foundational documents—the Society for Ecological Restoration International Primer on Ecological Restoration (Primer). Through a series of organized discussions, we assessed the Primer for its currency and relevance in the modern field of ecological restoration. We focused our assessment on the section entitled "The Nine Attributes of a Restored Ecosystem" and grouped each of the attributes into one of four categories: species composition, ecosystem function, ecosystem stability, and landscape context. We found that in the decade since the document's inception, the concepts, methods, goals, and thinking of ecological restoration have shifted significantly. We discuss each of the four categories in this light with the aim of offering comments and suggestions on options for updating the Primer. We also include a fifth category that we believe is increasingly acknowledged in ecological restoration: the human element. The Primer is an important document guiding the practice of restoration. We hope that this critical assessment contributes to its ongoing development and relevance and more generally to the development of restoration ecology, particularly in our current era of rapid environmental change.

Key words: ecosystem function, ecosystem stability, goal setting, landscape effects, SER Primer, species composition.

Introduction

It is now widely recognized that ecological restoration forms an integral part of global conservation efforts and associated policy frameworks (Wilson 1992; Suding 2011). One document—the Society for Ecological Restoration (SER) International Primer on Ecological Restoration (2004) ("Primer" in all text following)—represents an important foundation in the field, providing definitions and guidelines for the science and implementation of ecological restoration. The document was the product of a number of scientists' and practitioners' efforts and has been used to define restoration at an international scale (Nellemann & Corcoran 2010; IUCN 2011). The document had multiple original goals: to summarize and provide an overview of the field, to present the first comprehensive definitions of the science, to provide guidelines for practitioners, and/or to outline the "ideal" goal of ecological restoration.

In the decade since the Primer's inception, theory and practice of ecological restoration have advanced immensely (Brudvig 2011; Van Andel & Aronson 2012). For this key document to remain relevant and useful, it must continue to reflect current ecological thinking, as recognized by SER's process of updating the Primer. Our research group, the Ecosystem Restoration and Intervention Ecology Research group (ERIE) at the University of Western Australia (UWA), aimed to examine whether and how the existing Primer, as an encapsulation of the essential elements of restoration ecology, resonates with, or falls behind, modern ecological knowledge and restoration practice. We focused on one section of the Primer: the "Nine Attributes of Restored Ecosystems." These attributes outline a "basis for determining when restoration has been accomplished" (SER 2004) and thus should clearly encapsulate the goals of restoration.

Participants were invited from a broad group of people associated with ERIE: students, post-doctoral researchers, professors, and practitioners (any person who coordinates restoration projects through work with government, industry, or community organizations) directly within the group as well as research collaborators at UWA and Murdoch University. We did not actively gather experts outside of our affiliates and collaborators. In an initial group discussion, we went through the

[1]School of Plant Biology, University of Western Australia (M090), 35 Stirling Highway, Crawley, WA 6009, Australia
[2]Address correspondence to N. Shackelford, email nancy.shackelford@gmail.com
[3]School of Biological Sciences and Biotechnology, Murdoch University, 90 South Street, Murdoch, WA 6150, Australia
[4]Science Directorate, Kings Park and Botanic Garden, Fraser Avenue, West Perth, WA 6005, Australia
[5]School of Environmental Science, Murdoch University, 90 South Street, Murdoch, WA 6150, Australia

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Table 1. The Nine Attributes of Restored Ecosystems as listed in the Primer and the designated category utilized for discussion.

Number	*Attribute*	*Category*
1	The restored ecosystem contains a characteristic assemblage of the species that occur in the reference ecosystem and that provide appropriate community structure.	*Species composition*
2	The restored ecosystem consists of indigenous species to the greatest practicable extent. In restored cultural ecosystems, allowances can be made for exotic domesticated species and for noninvasive ruderal and segetal species that presumably co-evolved with them. Ruderals are plants that colonize disturbed sites, whereas segetals typically grow intermixed with crop species.	*Species composition*
3	All functional groups necessary for the continued development and/or stability of the restored ecosystem are represented or, if they are not, the missing groups have the potential to colonize by natural means.	*Ecosystem function*
4	The physical environment of the restored ecosystem is capable of sustaining reproducing populations of the species necessary for its continued stability or development along the desired trajectory.	*Ecosystem function*
5	The restored ecosystem apparently functions normally for its ecological stage of development, and signs of dysfunction are absent.	*Ecosystem function*
6	The restored ecosystem is suitably integrated into a larger ecological matrix or landscape, with which it interacts through abiotic and biotic flows and exchanges.	*Landscape context*
7	Potential threats to the health and integrity of the restored ecosystem from the surrounding landscape have been eliminated or reduced as much as possible.	*Landscape context*
8	The restored ecosystem is sufficiently resilient to endure the normal periodic stress events in the local environment that serve to maintain the integrity of the ecosystem.	*Ecosystem stability*
9	The restored ecosystem is self-sustaining to the same degree as its reference ecosystem, and has the potential to persist indefinitely under existing environmental conditions. Nevertheless, aspects of its biodiversity, structure, and functioning may change as part of normal ecosystem development, and may fluctuate in response to normal periodic stress and occasional disturbance events of greater consequence. As in any intact ecosystem, the species composition and other attributes of a restored ecosystem may evolve as environmental conditions change.	*Ecosystem stability*

attributes and decided that, rather than consider each attribute separately, we would group them into four broad ecological categories that matched broad themes frequently considered in the wider literature: species composition, ecosystem function, ecosystem stability, and landscape context (Table 1). Volunteer subgroups of four to five participants performed an informal literature review within each category, and led a 60–90 minute long discussion session with the broader group. Discussion sessions had 10–12 participants and included (on average) researchers (∼22%), practitioners (∼24%), doctoral candidates (∼36%), and post-doctoral researchers (∼18%) (see Appendix, Supporting Information, for exact numbers in each session). Following each discussion session, the main points arising were summarized and circulated. These formed the basis for the initial drafting of this paper, by those discussion participants most excited and well-versed in the topics under consideration. The discussion sessions highlighted a number of themes common across all categories, and in particular the importance of human agency and social aspects of restoration emerged as an important issue deserving attention. Hence this was included as a fifth theme in the further development of the paper.

This manuscript is structured into five sections. The first four sections are dedicated to each of the attribute categories previously mentioned. The fifth section appraises the human element in restoration. This topic consistently arose as an important consideration in all of our discussions but is not explicitly addressed in the existing Primer attributes. The use of these sections allowed ecological theories to be conceptually linked with a number of the attributes, many of which had some cross-over.

We found that although the Primer captures many of the ideas pivotal to restoration ecology, it requires changes to incorporate the recent advances in ecological theory. We discussed those advances and outlined specific suggestions for the ongoing development of the Primer. Underlying many of the discussed issues is the inevitable reality that is calling for a new understanding of restoration in the modern world—that we are experiencing rapid and often unpredictable environmental change. Hence, many of our suggestions explore ways to respond to modern global change in terms of the desirable attributes of a restored ecosystem.

Species Composition (Attributes 1 & 2)

Restoring the species composition of a reference ecosystem is probably the single goal of restoration that is more concrete and thus seemingly most easily implemented (Ruiz-Jaen & Aide 2005). The Primer suggests that the compositional attributes of a restored system are the presence (and abundance) of species from the reference system that consist of "indigenous species to the greatest practicable extent." Though apparently straightforward, this goal can present some conceptual and practical difficulties, which should be explicitly acknowledged in the Primer. First, biotic and/or abiotic constraints might impede the establishment of indigenous species

(Hobbs & Harris 2001). For instance, re-establishing native species in disturbed arid landscapes is heavily constrained by a recruitment bottleneck at the seedling emergence phase, with both the seed material and abiotic environment contributing to very low plant establishment rates (James et al. 2011). New techniques such as seed agglomeration (Madsen et al. 2012) present potential methods to overcome those constraints. However, there is still much development and research necessary to optimize species establishment efforts. Second, there is a degree of ambiguity in the term "native." Species that are classified as "native" might change dependent upon the scale of consideration (Warren 2007) or with range shifts due to changing environmental conditions (Walther et al. 2009). Potential techniques help to track species distributions include mapping "projected dispersal envelopes" based on biogeography and niche theory, thus defining shifting "native" ranges irrespective of direct human involvement (Webber & Scott 2011).

More broadly, we argue that restoration goals both include and go beyond achieving the species composition of a historic or reference site. By focusing on ecosystem function and stability, species composition becomes both a goal and a tool of restoration. Species composition often underlies many other goals such as function (Chapin et al. 1997), stability (Tilman & Downing 1996), and ecosystem services (Kremen 2005). Feasibility of achieving these goals may depend on selecting a species set for restoration that is not solely informed by a particular reference site or historic composition. Looking outside of the reference system for species to include in restoration includes a range of options, from mild to extreme deviation from the reference species pool. Mild deviations could include restoring local species from non-local provenances (e.g. collecting seeds from drier parts of species ranges for restoration under a drying climate), while extreme deviations could include the deliberate use of non-native species to achieve certain restoration goals (e.g. use of non-native birds to pollinate native plants in Hawaii [Cox 1983]). However, decisions regarding the introduction of non-native species to achieve restoration goals must be tempered by the known risks and repercussions of non-native species in ecosystems (Simberloff 2005; Alyokhin 2011).

Ecosystem Function (Attributes 3, 4, & 5)

Although the Primer acknowledges that the ecosystem may evolve as environmental conditions change, it does not address rapid current environmental changes (Vitousek et al. 1997; Rockström et al. 2009) and how these might impinge on our ability to restore ecosystems (Hobbs & Cramer 2008). As previously highlighted, the focus on historic or reference species composition may be limited by rapid environmental changes that make it difficult to identify a reference ecosystem in the first place. Thus, in some cases, it may be appropriate to emphasize functional goals over goals based on species composition. For example, functional goals might be appropriate for urban wetlands where high levels of human visitation prevent the restoration of obligate wetland species (Ehrenfeld 2004). Equally, for degraded rangelands in the United States, managers tend to focus on restoring soil stability, hydrology and biotic integrity rather than species composition (Pyke et al. 2002). Functional goals have long been emphasized in restoration after mineral exploration and mining where it is often necessary to reconstruct soil, slope, and landscape hydrology before species can be restored (Bradshaw 1997). In these contexts, the key goal is to restore the abiotic processes that sustain a functioning ecological system (Jax 2005).

The Primer states that most ecosystem functions "cannot be ascertained without research efforts that exceed the capabilities and budgets of most restoration projects." Traditionally, functional goals have been stymied by the difficulty of translating such theory into practice and a lack of means to measure success (Ruiz-Jaen & Aide 2005). However, recent progress is being made. For example, a recent study of plant-pollinator networks in Scotland suggests how functional goals might be achieved via a combination of theoretical and empirical approaches (Devoto et al. 2012). Additionally, practical methods in ecosystem science have developed considerably in the last 10 years (Getzin et al. 2011), and with it the methodology for measuring ecosystem functions (Fry 2006). For instance, Moreno-Mateos et al. (2012) recently reviewed both structural and functional aspects of wetland restoration and highlighted the relative ease with which some of them can be measured. Perhaps the most critical development for restoration practice has been the development of remote sensing tools to measure ecosystem function at the landscape scale. For example, remote sensing can be used to detect changes in biogeochemistry associated with plant invasions (Asner & Vitousek 2005) and has the potential to be developed as a low-cost tool for measuring carbon storage at the regional scale (Asner et al. 2011).

Ecosystem Stability (Attributes 8 & 9)

Potentially one of the holy grails of site-focused restoration efforts is achieving a level of self-renewal and capacity to persist in the face of disturbance (fire, drought, trampling, etc.). Restored ecosystems are generally expected to be "stable." However, ecosystem stability is a multi-faceted concept that is notoriously difficult to measure (Ives & Carpenter 2007), and has also to be reconciled with the observation that all ecosystems are dynamic. Therefore, one must first be clear about which aspects of stability are desirable. The Primer deals mostly with two facets of stability, resistance and resilience, but does little in the way of offering an applicable distinction between the two or suggestions on implementation and measurements of success.

Ecosystem resistance can most easily be conceptualized in terms of extant individuals persisting through disturbance, such as established trees surviving drought or fire, but can also be thought of in functional terms such as constancy of ecosystem services such as clean water or air. Resistance is important as established individuals may contribute disproportionately in terms of producing propagules/offspring or habitat features like shade or nesting structures (Merritt & Poff 2010). Indeed, development of resistance to subsequent disturbance (e.g. reintroduction of fire, Herath et al. 2009) in a restoration context, likely, is critical to success and thus its measurement central to evaluating outcomes. For example, post-restoration resistance in fire-prone species-rich shrublands can be achieved through planting resprouting species, as they comprise dominant structural elements, are a large portion of the plant community, and display high survivorship through fire and low recruitment rates (Herath et al. 2009). Evidence suggests that, as with wetlands (Moreno-Mateos et al. 2012), resistance may increase with time since restoration but does not reach that of reference sites (Herath et al. 2009).

Ecosystem resilience, on the other hand, may be strongly affected by pulse disturbances, yet resilient ecosystems are able to reorganize and recover their original structure and functions (Folke et al. 2004). Similar to achievement of ecosystem function (see previous section), restored ecosystems can be made more resilient by promoting functional redundancy—the number of species within a given functional group (Walker 1992) and response diversity—the diversity of responses to disturbance by species that contribute similarly to a particular function or service (Elmqvist et al. 2003). For example, in the case of terrestrial plants, traits that influence responses to disturbance include those linked to regeneration (e.g. regeneration strategy, seed dispersal, seed dormancy). High response diversity ensures that no single disturbance wipes out an entire functional group following a specific disturbance (e.g. varying fire response strategies in tree species important for wildlife habitat [Fontaine et al. 2009]).

A limitation of this trait-based approach to resilience is that it requires extensive functional-trait data, which are unavailable in most restoration projects (Laliberte et al. 2010). Alternatively, easily measured ecosystem properties can be used as "leading indicators" of decreasing ecosystem resilience (Brock & Carpenter 2010). For example, the rising within-year variance in lake-water phosphorus can indicate a loss of resilience and is a precursor to eutrophication (Carpenter & Brock 2006). This type of approach has been easily articulated in aquatic and marine systems (Pandolfi et al. 2003), but its application to terrestrial ecosystems is still challenging (Bestelmeyer et al. 2011).

Landscape Context (Attributes 6 & 7)

The importance of a landscape approach in restoration science and practice has been widely recognized (Holl et al. 2003; Young et al. 2005). Although the attributes echo the consensus in current ecological literature, they do not explicitly indicate important landscape aspects that influence the restored ecosystem and that may be controlled and/or manipulated toward a desired restoration outcome. For instance, no explicit consideration is given to the influence in restoration of site size. Small sites or patches support less species (species-area relationship) and are more vulnerable to edge effects and to the synergistic impact of multiple factors and disturbances (Ewers & Didham 2007). Hence, the actual size of a site to be restored may constrain restoration success, for instance, by impeding the establishment of viable populations of a key desired species or trophic level (Morrison et al. 2010), or by preventing desired environmental conditions due to edge effects. In such cases, restoration of sites larger than a certain area threshold (e.g. depending on the key species requirement) could be prioritized. Moreover, intervention could target, for instance, the expansion of the current site area through restoration of its surroundings (Thomson et al. 2009) or the restoration of the key species-specific habitat within the site.

Additionally, the Primer makes no mention of landscape connectivity and permeability, that is the availability of the same habitat type or other land use allowing the movement and flow of individuals and genes between patches and across the landscape. The importance of landscape connectivity and permeability to species movement across the landscape is evident in both aquatic (Tanner 2006) and terrestrial (Llorens et al. 2012) ecosystems. These landscape attributes have major relevance to restoration because they can increase the colonization of the restored ecosystem by native species and also allow the spread and invasion by non-native species, diseases, and predators (Simberloff & Cox 1987; Holl & Crone 2004; Beechie et al. 2008). Moreover, landscape connectivity and permeability can be manipulated so that specific restoration goals can be achieved. For instance, bird habitat in an urban reserve can be enhanced through restoration of neighboring woodlands and the use of native plant species in residential gardens (Goddard et al. 2010). Additionally, refugia should be prioritized for restoration, as they are crucial for the landscape-scale maintenance of biodiversity in the face of rapid environmental change (Beechie et al. 2008; Renton et al. 2012).

Finally, landscape composition, that is the type and characteristics of the surrounding land uses, can strongly influence the restored ecosystem (Ward et al. 2002; Allan 2004). The Primer recommends, as much as possible, those potential threats from the surrounding landscape be eliminated or reduced. However, we argue that a more integrative approach, one that minimizes the effect of external factors but also adjusts restoration goals and efforts to the reality of their presence, may be more effective. For example, Yates et al. (2000) found that simply removing livestock from grazed remnant woodlands in the south-western Australia wheatbelt was not enough for their restoration and that other interventions designed to capture and increase resource retention were required.

The Human Element

Restoration is an attempt by people to intervene in an ecosystem that is perceived as degraded or damaged in order to protect or reinstate characteristics that are considered valuable. Hence, human intervention and values are implicit elements of restoration. Although this is recognized at points in the Primer, neither the actions nor values of people are explicitly included in the attributes of a restored system as defined by the Primer. Similarly, characteristics relating to social issues that may affect restoration success are absent from the list of attributes, despite these being a major element in many projects (Hallett et al. 2013 this issue).

There is an increasing acceptance of the role people play in shaping most ecosystems. An obvious example is the ongoing interplay between human management and ecosystem form and function in European systems, where people have been actively managing landscapes for millennia, whereas less obvious examples are the sometimes forgotten influence of indigenous peoples in the New World (Mann 2005). People will remain an important aspect in many or most ecosystems into the future, especially given the increasing human footprint (Zalasiewicz et al. 2010). There will undoubtedly continue to be cases where little intervention by people occurs following the initial restoration treatment, such as, for instance, in mine-site restoration in remote arid areas where population density ranges between 0 and 0.2 person/km^2 (Ezcurra 2006). However, ongoing intervention may be required in many ecosystems to maintain a desired state or trajectory. Indeed, in some instances, restoration takes the form of reinstating past management regimes—for instance in maintaining open meadows or grasslands in many parts of Europe by mowing and grazing (Walker et al. 2004; Woodcock et al. 2005), or by reinstating Aboriginal fire regimes in savannah landscapes in Australia (Whitehead et al. 2009). Hence in these cases, an important attribute of the restored system is the reinstatement of these management practices.

In other cases, incorporating human values may itself be a goal of the restoration. For example, urban restoration projects can explicitly set out to engage people in interacting with local ecosystems (Standish et al. 2012). Important elements of this engagement include community involvement in goal setting, restoring people's connection to nature, and reinforcing the place of people as part of nature rather than being apart from nature. One study of restoration value to the community found that social goals matched well with ecological goals (Petursdottir et al. 2012), implying that restoration may potentially incorporate social factors without necessarily losing ecological considerations. Additionally, large restoration projects often require the involvement of stakeholders and the scale of the threat or disturbance requires cooperation across multiple government agencies and/or landholders. This is particularly obvious in river and wetland restoration projects (Comín et al. 2005; Gramling 2012). Restoration projects need to acknowledge the differing views of stakeholders prior to commencement to ensure that projects do not fail due to lack of communication and outcomes that do not address the goals of multiple parties.

Additionally, recent restoration efforts have begun to focus more heavily on ecosystem services—processes or functions of an ecosystem that provide benefits and values to people (Bullock et al. 2011; Suding 2011). By explicitly considering ecosystem services, the definition of ecosystem function broadens to include those functions valued by people (Jax 2005). This approach may present both conflicts and opportunities for ecological restoration goals (Bullock et al. 2011). Attaining high levels of different functions may be prevented by trade-offs (Nelson et al. 2009; Zavaleta et al. 2010) and decisions will need to be made about which functions ought to be prioritized for restoration. While science can inform these decisions (Hector & Bagchi 2007; Hillebrand & Matthiessen 2009; Isbell et al. 2011), ultimately, the answer will reflect the values and proclivities of the stakeholders that have vested interests in the project (Minteer & Collins 2005). For example, in parts of the world where food, firewood, and other key resources to sustain human populations are limiting, the focus is likely to be squarely on ecosystem services first and achieving the ecological attributes that allow these goals to be met.

Synthesis and Conclusions

Our analysis of the attributes of restored ecosystems as outlined in the Primer considered the utility, appropriateness and comprehensiveness of these attributes in the context of recent ecological thinking and increasing recognition of rapid environmental change. We have undertaken a critical analysis of the underlying science and ecological thinking of the document while also making some concrete suggestions for its continued development (Table 2). Though we grouped the original Primer attributes into a series of categories, there is considerable interrelation among each category just as with the attributes themselves. Further unraveling of the nature of the relationships among categories is an important area of continuing research. Some attributes and categories are much easier to measure than others. There is little point in advocating attributes that are poorly understood and hard to measure, but, if these can be related back to attributes that are more readily measured, they can nevertheless be incorporated into restoration goals.

The question of setting restoration goals looms large in decisions over which attributes to focus on and how these should be characterized. We have discussed the need for some plurality in the decision-making process because many different restoration goals are possible, depending on the context, scope and resourcing of particular projects. In particular, an expansion of goals to consider ecosystem services and human wellbeing seems essential in today's world, and especially in parts of the planet where restoration is undertaken to reinstate productive capacity in degraded land. In addition, goal setting requires consideration of what is feasible and appropriate given rapid environmental change (Hobbs 2007).

The question of goals for restoration relates strongly to the question of who sets these goals and undertakes the restoration. Restoration activities range from small, local activities carried out by individuals or community groups through to regional, country, and even global-scale activities involving multiple agencies and large numbers of people (Menz et al. in review). Ensuring that the Primer speaks to this range of audiences is critical for it to remain relevant as a touchstone for restoration. The audience for the original Primer was not made explicit and hence the assumption has to be that it was directed at all of these groups. While this is a laudable aim, and makes the

Table 2. A summary of specific suggestions for updating/editing the Attributes of Restored Ecosystems section in the SER Primer.

Category	*Suggestion*
Species composition	Expand goals beyond restoration of historic or reference sites to explicitly consider multiple other attributes of restored systems
	Acknowledge that the term "indigenous" or "native" refers to dynamic and not static species distribution ranges
Ecosystem function	Highlight particular importance of focusing on restoring ecosystem function under certain contexts such as changing environmental conditions
	Broaden definition of "ecosystem function" beyond "the dynamic attributes of ecosystems," including, for instance, the provision of ecosystem services
Ecosystem stability	Use trait-based measurements of functional redundancy and response diversity as a way to quantify the resistance and resilience of a restored ecosystem
Landscape context	Include attribute about ecosystem spatial configuration, importantly size
	Make explicit reference to landscape connectivity and permeability
	Consideration of potential threats from the landscape should incorporate both minimization/removal of those threats as well as the incorporation of their reality into restoration planning
Human element	Make explicit potential for permanent human involvement where appropriate
	Include attribute encompassing cultural or social values
	Include social influences in definitions of resilience/resistance
	Acknowledge the necessity of stakeholder buy-in
Further suggestions	
Highlight variability in relative importance of attributes within the restoration process based on project context	
Provide examples/case studies	
Offer ways to measure complex ecosystem properties such as function, resilience, resistance	

document general enough to be broadly useful to a wide range of people, it runs the risk of making it not particularly helpful in the specifics of any given context. Hence, the challenge is to maintain a degree of generality but to include more specific guidance that will assist in more limited contexts. This could be achieved, for instance, by providing examples and case studies of how particular attributes are used in specific situations. This change alone could greatly enhance the accessibility of the Primer to its many target audiences.

We do not attempt to provide alternative updated attributes here. Instead, we provide pointers to where the current attributes could be profitably modified, replaced, or supplemented. We hope that this contributes to an open and productive debate among all parties interested in ensuring the ongoing utility and endurance of one of the foundational documents for ecological restoration.

Implications for Practice

- Through a series of organized discussions, we assessed the Primer for its currency and relevance in the modern field of ecological restoration.
- We suggest that the Primer needs to capture the wider range of goals and aims of individual restoration efforts, if it is to maintain relevance in the field.
- Ecological science behind complex concepts, such as ecosystem stability, has advanced in the past decade. To keep current, new definitions and measurement techniques should be clarified and considered in the Primer.
- To this end, we offer a number of suggestions for the Primer updating process.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix. Participant information.