Design Criteria for Process-Based Restoration of Fluvial Systems

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Process-based restoration of fluvial systems removes human constraints on nature to promote ecological recovery. By freeing natural processes, a resilient ecosystem may be restored with minimal corrective intervention. However, there is a lack of meaningful design criteria to allow designers to evaluate whether a project is likely to achieve process-based restoration objectives. We describe four design criteria to evaluate a project's potential: the expansion of fluvial process space and connectivity lost because of human alterations, the use of intrinsic natural energy to do the work of restoration, the use of native materials that do not overstabilize project elements, and the explicit incorporation of time and adaptive management into project design to place sites on recovery trajectories as opposed to attempts to "restore" sites via a single intervention. Applications include stream and infrastructure design and low-carbon construction. An example is presented in California's Sierra Nevada foothills.

Keywords: floodplain, meadow restoration, stream restoration, multithread channel, carbon emissions

Fluvial ecosystems are some of the most diverse and productive systems on Earth (Naiman et al. 1993). They are the hydrogeomorphic template on which most early civilizations arose and they continue to be heavily used (Solomon 2010). Many of the benefits these systems provide to human society, including biological diversity and productivity, have been degraded, and their recovery is limited within the confines of current infrastructure and land uses (Bernhardt and Palmer 2011). As such, there is tremendous societal interest in recovering degraded fluvial ecosystems, and billions of dollars are spent annually on attempts to restore the services they provide (Bernhardt et al. 2005, Ring 2018).

The science of ecosystem restoration is relatively new, and many initial efforts have been primarily focused on designing projects to achieve a specific outcome, form, or habitat feature (Palmer et al. 2005). As restoration science has evolved, we have come to understand that ecosystems provide greater function over the long term when the dynamic forces that create and maintain them are allowed to operate. We have also learned that designing for static conditions provides limited ecological value and requires ongoing management and energy inputs to maintain specific geomorphic structural conditions (Kondolf 2011). Sustainable restoration outcomes are more likely when placed soundly within a broad ecosystem context that allows natural biophysical interactions to drive recovery and requires relinquishing some control over site-specific outcomes to learn from those interactions (Apfelbaum and Haney 2012, Palmer et al. 2014a).

It has been hypothesized that the idealized habitats sought in conventional restoration design may be better achieved when managers influence natural processes and obtain feedback with which they then revise subsequent restoration interventions (see Ross et al. 2015). This iterative and interactive approach acknowledges a lack of complete system understanding at the outset of implementation. Such an approach has been employed with great success in other fields. For example, the early history of flight control was plagued by a "frustrating search for inherent stability," which was solved when the Wright brothers suggested that pilots be "provided with sufficiently powerful controls with which to balance and steer" (McRuer and Graham 1981). Similarly, many ecosystem restoration designers have sought the inherent stability that early flight engineers attempted to create (Ross et al. 2015). However, this static design approach is arguably as inappropriate for managing complex ecosystems as it is for airplanes. By embracing feedback signals and dynamic controls in the design and management of ecosystems, as did the Wright brothers for airplanes, we argue that restoration scientists and engineers will observe similar gains in ecosystem "performance."

The search for inherent stability during the project design phase often and unknowingly conflicts with objectives aimed at restoring natural processes. Design criteria are specific measurable attributes of a project that help designers identify such conflicts and ensure that appropriate restoration objectives are considered during the design phase (Miller and Skidmore 2003). A challenge for restoration science is how to develop design criteria for fluvial ecosystem restoration projects intended to respond dynamically to stochastic disturbances such that there is a range of acceptable

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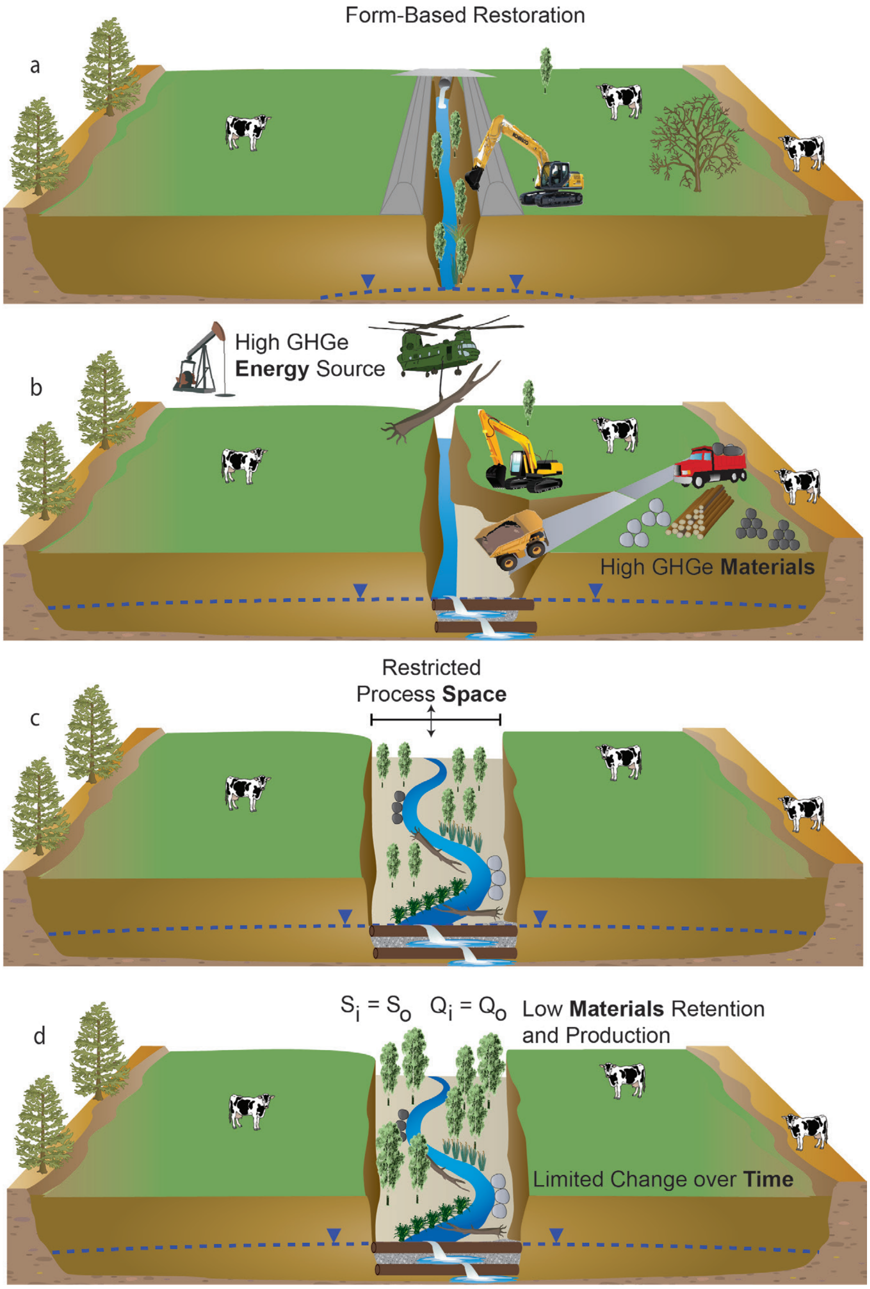

Figure 1. Illustration of a form-based restoration design whereby: (a) Infrastructure constraints are removed using heavy equipment. In this example, infrastructure such as levees and an upstream culvert blocking fish passage are removed. (b) Instream work is extensive and heavily engineered, requires heavy equipment, and a large carbon and disturbance footprint. In this example, an inset floodplain is created, which keeps the water table depressed and limits the amount of process space that can be reconnected. (c) Extrinsic materials such as rock and large wood are brought in to help create a stable channel form that is in equilibrium with respect to sediment transport so that erosion and deposition within the reach are minimal. The inset floodplain area is designed with a single-thread bankfull channel typically flooding once every 1–2 years. Vegetation growth is suppressed because the groundwater level is rarely at or near the surface. (d) The channel remains stable over time and opportunities for habitat-forming processes are limited.

structural outcomes and a broad time frame for achieving outcomes. That is, what criteria do we apply toward design of ecosystems that efficiently use intrinsic energy and materials to develop a high level of structural complexity across large spatial scales and that sustain themselves over time, similar to historical conditions (Walter and Merritts 2008).

Form-based restoration design criteria for fluvial systems are established and are largely based on the reference condition concept, whereby a natural stream, thought to represent what should be the natural condition of the treatment reach, is used as a template for the restoration design (figure 1; Leopold et al. 1964, Dunne and Leopold 1978, Rosgen 1996). This approach focuses largely on channel form and generally designs for equilibrium conditions such that sediment inputs and outputs are approximately equal, and floodplains are infrequently inundated, usually only once every 1–2 years. Design criteria aimed at constructing a reference reach will quantify the expected stability and form of a stream channel and determine acceptable tolerances or limits of channel bed and bank deformation, stability of constructed features and channel dimensions (Miller and Skidmore 2003). Such narrow design tolerances on stream habitat form may preclude the objective or even evaluation of using natural process to rebuild habitat over time (Mitsch and Jorgensen 2003, Beechie et al. 2010, Palmer et al. 2014a, Johnson et al. 2020). For example natural and stochastic occurrences such as avulsions, wood jams, beaver dams, and other dynamic processes that create obstructions, raise water tables, create multithread channels, and alter sediment dynamics may not be capitalized on for the design because they create uncertain structural outcomes that make it hard to measure project success or that conflict with narrow design limits.

Process-based fluvial ecosystem restoration is an alternative paradigm to form-based restoration design (figure 2). Process-based restoration recognizes that streams are not simply a channel but a complex dynamic and evolving system that includes all of the area on and near

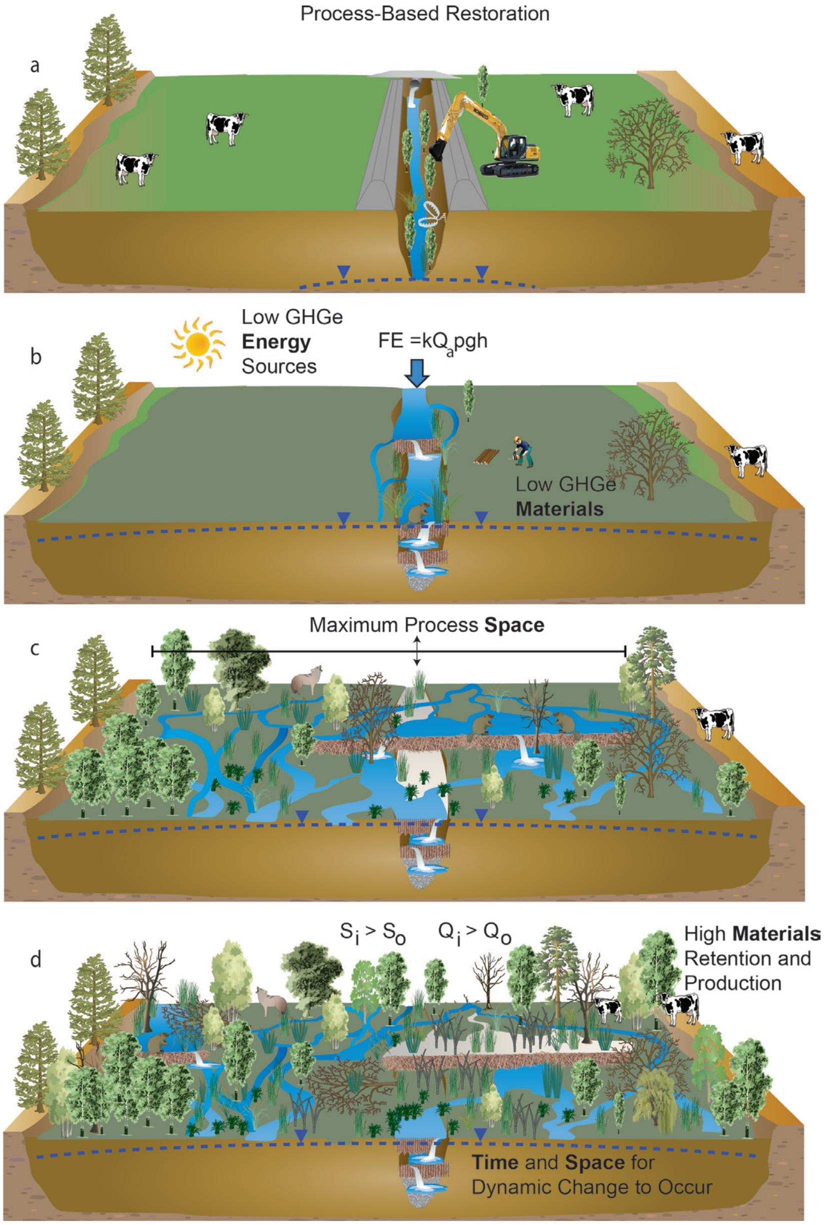

Figure 2. Illustration of a process-based restoration design whereby: (a) Infrastructure removal, some using heavy equipment, is an explicit focus to create as large an area as possible for natural habitat forming fluvial processes to occur. In this example, levees and an upstream culvert blocking fish passage are removed, cattle are removed temporarily, and beaver trapping ceases. (b) Instream work may be extensive but relies on stream energy and natural materials and has a small carbon and disturbance footprint. In this case beaver dam analogues raise water tables to the surface of the floodplain and to encourage side channel formation and sediment deposition (see Pollock et al. 2014). (c) Fluvial energy, sediment, and vegetation develop a complex multichannel system. A productive and biologically diverse system is created; beaver colonize the area, adding further hydrogeomorphic complexity; predators return. (d) Over time the system remains dynamic, with habitat elements forming and disappearing, and reappearing elsewhere.

a valley floor that has been affected by or directly affects fluvial processes, which we refer to in the present article as *process space*. In this framework, the current location of a stream channel is recognized as an ephemeral structure that may exist elsewhere in the future or may not even exist in a form that is recognizable as a channel, because disturbances create a structurally complex system with high ecosystem benefits that is reflective of historic conditions (e.g., anastomosing or stage 0 condition; Cluer and Thorne 2013, Pollock et al. 2014, Chone and Biron 2016). A process-based approach focuses expectations not so much on specific structural outcomes as on evidence that natural fluvial processes, such as sediment transport, flooding, and biologically mediated disturbances are creating a complex, self-sustaining ecosystem.

In this article, we assert that meaningful design criteria for process-based restoration projects can be developed from established standards and principles (table 1; Palmer et al. 2005 and Beechie et al. 2010). We argue that a priori criteria can be developed for assessing how well a proposed restoration project will likely use the four fundamental components inherent in any restoration project—space, time, materials, and energy—to successfully redirect fluvial ecosystem trajectories toward a complex and resilient condition with high ecological value.

We focus on restoration of fluvial systems where biological influences are high relative to hydrologic and geomorphic influences (Castro and Thorne 2019). These are typically low-gradient unconfined and semiconfined stream and river valley bottoms. We illustrate how the design criteria translate into measurable restoration with an example project from California's Sierra Nevada foothills.

Design criteria

We propose four design criteria for process-based restoration projects, framed on the fundamental parameters of space, energy, materials, and time. Application of the criteria requires designers to incorporate adaptive learning and acknowledge that stochasticity and uncertain outcomes are inherent to any restoration project that seeks high ecological functionality (Norland et al. 2018). We start with the definition of each criterion and follow with examples of its implementation. Although each criterion is described independently, they are all interdependent pieces of process-based design.

Table 1. Differences in stream restoration design practices when applying the process-based standards and criteria compared to conventional form-based restoration standards and criteria

Conventional objectives[a]	Process-based translation[b]	Form-based practices	Process-based practices
Increase habitat quantity and meet structural form targets.	Increase space and connectivity for fluvial and biological process.	Modify existing habitat with heavy machinery by manipulating onsite material or importing rock and fill material to increase meanders, armor streambanks, and fill incised channels.	Modify infrastructure to accommodate greater fluvial dynamics (e.g., remove levees, expand flow options at road crossings).
Protect native plants and animals or mitigate for their removal.	Protect native plants and animals and work with them to improve habitat conditions for expansion.	Relocate or temporarily store native vegetation and sensitive animals for postconstruction release. If infeasible, mitigate by planting or replacing more than were lost.	Leave vegetation and sensitive animals in place. Observe how their habitat is created or maintained by the system's physical and biological processes and work with those processes to increase and improve habitat conditions.
Apply stabilizing structures to control dynamism and resist change to habitat form.	Use of stream energy and onsite materials to build and rework habitat over time.	Use designs and materials to resist flood forces, erosion or deposition (e.g., cross vanes, J hooks, rock riffle augmentation, and toe wood).	Partner with nature to evolve habitat. Maximize native plant production and protect ecosystem engineering species. Use fluvial energy to achieve sediment transport goals. Save and propagate beaver associated plants.
Use engineering designs to construct habitat during one treatment period.	Refrain from rapid but heavy-handed techniques; rather, apply adaptive approaches over time.	Apply engineered design during one construction period and monitor effect. Repair structures or channel forms that succumb to fluvial forces with heavy machinery.	Limit construction to infrastructure areas. Build ephemeral habitat structures using natural materials found onsite to evoke a process response. Learn from and adapt to the system's response to adjust structures to encourage desired change.

[a]Rosgen 1996, Shields et al. 2003. [b]Palmer et al. 2005, Mitsch and Jorgensen 2003, Apfelbaum and Haney 2012.

Fluvial process space criterion: Project actions increase the spatial extent of fluvial processes and connectivity lost because of human alterations. Much of the degradation to fluvial ecosystems involves confining and disconnecting vertical, lateral, and longitudinal processes, such as natural sediment movement, flooding, and fish and wildlife migration. Such disconnections arise from construction of dikes, levees, roads, rail lines, and other human infrastructure (Kondolf et al. 2006, Wohl et al. 2019). Grazing, mining, and timber management also affect vegetation and topography, with consequences for process space connectivity. Key to success of process-based restoration projects is ensuring that there is sufficient space for natural fluvial processes to occur. This allows for dissipation of stream energy, sediment deposition and erosion, and increased surface–ground water connections in accord with the natural hydrogeomorphic and biological potential of the site (figure 3). Reconnecting fluvial process space, increases the interaction of floodplain vegetation with hydrogeomorphic processes, adding further spatial and temporal complexity to patterns of flooding, sediment transport and erosion, which enables a river system to create and restructure habitat (figure 4; Junk et al. 1989, Piégay et al. 2005). Fluvial process space has been variously described as the channel migration zone, *espace de liberté* (freedom space), and erodible corridor (Brierley and Fryirs 2009, Biron et al. 2014).

We do not propose rigid criteria for what constitutes sufficient process space but suggest that a relative determination can be made if three pieces of data are gathered from the project site: the historical extent of process space, the extent of currently disconnected process space, and the current channel width.

The historical process space defines the maximum potential available space for ecosystem recovery. The historic area typically includes the valley bottom, adjacent tributaries, and alluvial fans that could interact with flowing water in the project area (Fryirs et al. 2007, Prominski et al. 2013). Helpful resources for defining historical process space include detailed topographic relief maps from LiDAR, sequential aerial images (e.g., from Google Earth, the US Department of Agriculture, and the US Geological Survey), LiDAR-derived detrended elevation models (Powers et al. 2019), historical photos, soil and topographical maps, and site surveys. Tributaries and connected hillslopes that influence bottomlands can be identified with established catchment-, valley-, and reach-scale analysis (Wohl and Merritts 2007, Wheaton et al. 2015, Kondolf and Piégay 2016).

After identifying the entirety of the historic process space, the subset of disconnected process space is then delineated. In many cases, the disconnected process space includes the historical process space, less a narrow corridor around an inset stream channel constrained by incision or infrastructure such as riprap, dikes, levees, fences, roads, and train tracks.

Finally, channel width is a useful metric to gather because it provides a metric of confinement for current conditions relative to historic conditions. In general, we consider a stream

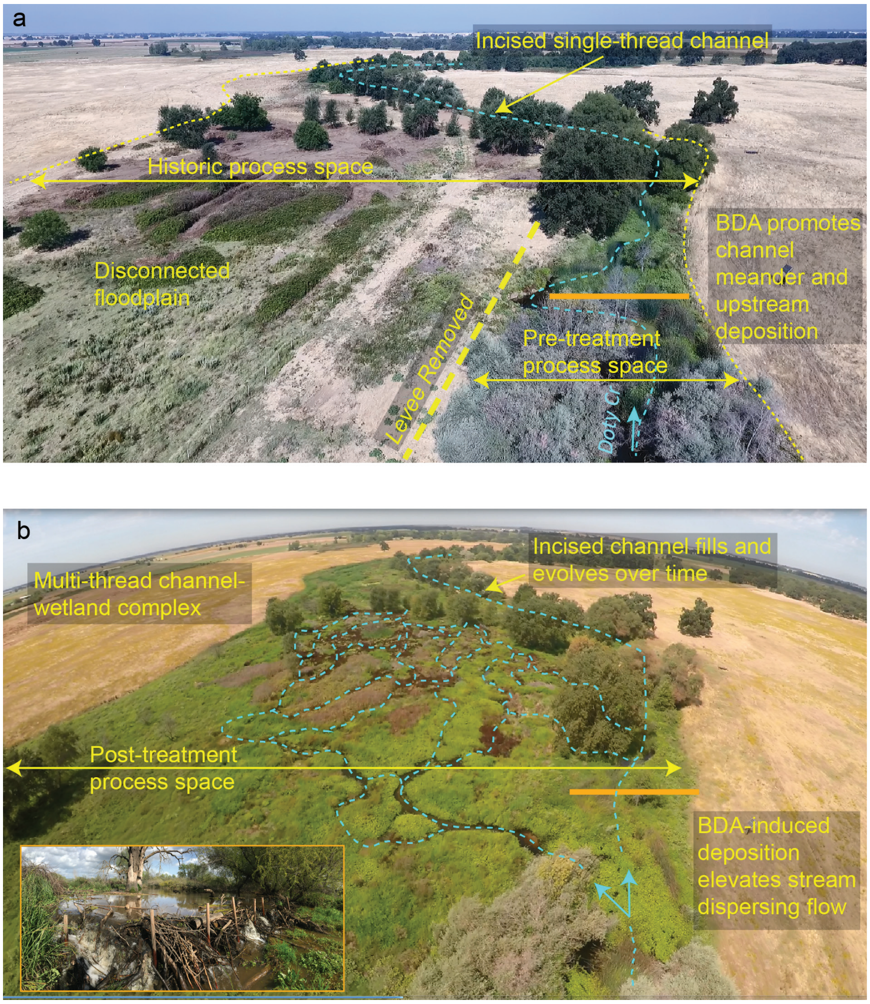

Figure 3. Doty Ravine Creek, California project area (a) in August 2017 before the floodplain was reconnected (b) in August 2019 after the floodplain was reconnected. Restoration design elements are highlighted on images along with gains in process space and stream recovery in response to restoration actions. Photographs: (a) Drone image by Placer Land Trust, (b) drone image by Matt Hamman.

confined if it has less than 4 channel widths of process space, moderately confined if the channel is less than 10 channel widths of process space and essentially unconfined if it is over 20 channel widths of process space (Beechie et al. 2013).

Once delineated, a comprehensive investigation of potential source problems that prevent reconnection of the predisturbance process space is undertaken. Again, LiDAR and aerial imagery are useful for detecting topographical anomalies not easily observed on conventional maps or in the field. For example, open-source software can be used to unite high-resolution terrain maps with detailed streamflow analyses through a Google Earth platform to explore watershed features in three-dimensions and to pinpoint disturbances in the stream network that interfere with connectivity (figure 5). Noted constrictions, flow path discrepancies, and incision points are then verified with directed field reconnaissance. Common source problems include used or abandoned roads, train tracks, levees, dikes, ditches, culverts, redirected flow paths, and unnatural stream armoring (e.g., riprap).

Source problems also include impediments to the natural biological forces necessary for ecosystem recovery. Examples of biological impediments include livestock grazing, depredation of beaver, and presence of nonnative species such as reed canary grass (*Phalaris arundinacea*) or signal crayfish (*Pacifastacus leniuscules*; Johnson et al. 2020). Once source problems are identified, a determination is made about which constraints can be removed, relaxed, or mitigated to meet process space goals. Overall restoration actions should result in a substantive net gain in process space to meet this criterion and ideally should move the channel to a completely unconfined condition.

Some systems may recover rapidly following removal or modification to infrastructure or bank stabilization (figure 3). The degree to which space and connectivity are restored will influence the rate and degree to which a project achieves ecological recovery. For example, the highly complex and diverse fluvial systems may require more than 20 channel widths of lateral floodplain space and restored longitudinal connections to upstream flood energy and sediment supply to sustain their complexity. Simpler morphologies (e.g., single thread channels) likely require at least of 4 channel widths of floodplain to achieve a minimal level of ecological recovery.

Reconnecting fluvial processes to disconnected process space is a necessary condition for restoring morphological complexity, but it may not always be sufficient to bring back lost biota, because many other factors come into play, such as intactness of the predisturbance seed bank, proximity to source areas for colonizing native species and adequacy of current flow regime to drive fluvial processes. There is little evidence to support the “build it and they will come” fallacy, which assumes that creation of suitable habitat by itself is sufficient to bring back desired species (Hilderbrand et al. 2005).

The delineation of fluvial process space is an assessment of the potential spatial scale of a project and encourages planning to focus less on channel form and more on gaining space and connectivity at a valley scale. For many projects, only partial occupation of the historic process space may be achievable, but this can still yield ecological benefits.

Figure 4. Images of (a) a flood pulse that reworked the Doty Ravine Creek floodplain in February 2018 providing new surfaces for (b) vegetation growth by July 2018. View looking upstream in the project area from 120 meters downstream of Gladding Road. Photographs: Damion C. Ciotti.

Energy criterion: Project actions capitalize on natural energy within the system to do the work of restoration and minimize the use of external mechanical energy. The restoration design criterion for energy requires consideration of the natural kinetic and potential energy such as water and sediment transport and storage, especially during floods, along with solar energy used to drive vegetative growth and metabolic energy expended by animals. Process-based design creatively maximizes the system's naturally available energy to meet restoration objectives while avoiding use of extrinsic energy (e.g., heavy equipment driven by fossil fuels) to do the work of restoration (Mitsch and Jørgensen 2003). This criterion parallels "green" architecture that uses naturally available energy (e.g., solar or wind) as much as possible for function of buildings (Guzowski 2010).

A good restoration designer understands when, where, and how the natural fluvial and biological energy in an ecosystem is created, stored, delivered and used—for example, how it generates and moves sediment, wood and other organic materials. The design uses this knowledge to set realistic time frames for achieving project objectives, set broad specifications for acceptable types and configurations of fluvial landforms, and recognize that working with natural energy sources requires acceptance of stochastic outcomes. This is a major departure from form-based restoration approaches that seek to rapidly create an assumed reference or predisturbance condition through substantial input of fossil fuel energy. Such construction projects require greater investment in fuel and project design to stabilize channel banks, streambeds, and habitat structures to ensure the designed channel form is not excessively altered during floods or by other natural processes such as beaver dam construction (Miller and Skidmore 2003, Pollock et al. 2014).

Most stream systems have tremendous fluvial energy. For example, the energy potentially available from flowing water on an annual basis can be estimated by the equation

$$FE = k \cdot Q_a \cdot \rho \cdot g \cdot h,$$

where FE is the fluvial energy measured in joules, k is the number of seconds in a year, Q_a is the mean annual discharge in cubic meters (m^3) per second, ρ is the density of water (1000 kg per m^3), g is the gravitational acceleration (9.81 meters per seconds squared), and h is the difference in elevation from the beginning to the end of a reach in

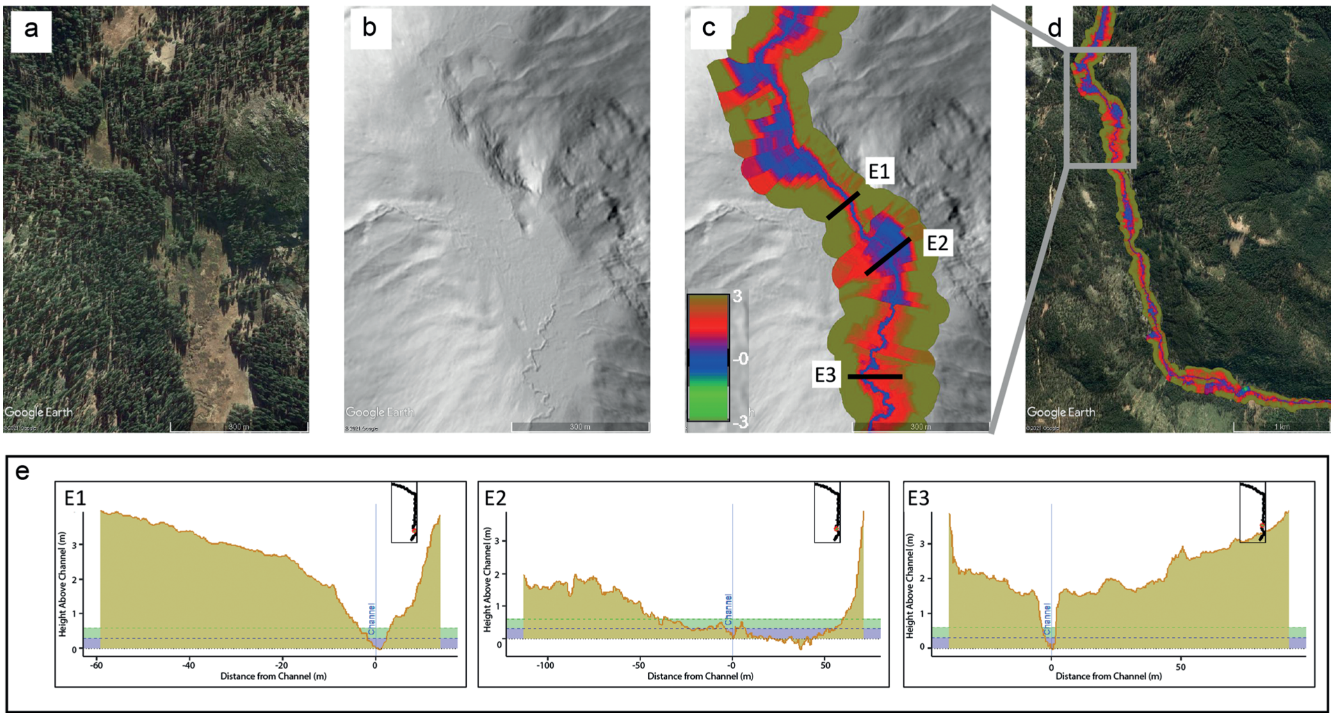

Figure 5. A series of images showing the different inferences that can be made between (a) aerial imagery (15 cm) that can highlight existing vegetation patterns, (b) hill shade LiDAR that effectively highlights sudden changes in elevation like incised channels, and (c) post processed LiDAR with detrended elevation profiles that can draw attention to connected and disconnectivity in a fluvial system. All three data sets at broader scales (d) can help focus planning, fieldwork, and restoration designs. (e) Three cross-sections used to create detrended elevation raster are highlighted showing a geomorphically constrained section of stream with minimal associated floodplain (low current and potential process space), a connected floodplain with limited stream confinement (high current and potential process space), and an incised channel, with limited connectivity between the primary flow path and the floodplain (low current but high potential process space).

meters. Even for small streams, the potential *FE* of one peak flow event typically well exceeds the energy input by heavy machinery for a conventional restoration project. If harnessed, floods may be employed to rapidly reorganize the landscape through sediment deposition and erosion to create new channels and fill incised segments. Partnered with the materials criterion (described below) to create strategic flow discontinuity and encourages greater interaction with biological and geomorphic processes and can cause dynamic habitat conditions with vegetated islands, channels, and deep pools. However, providing the system's energy a chance to rework channel networks requires designers accept uncertainties in the rate and extent of successional process and that narrow expectations for channel forms may not be met (Larsen et al. 2021, Nash et al. 2021). By evaluating catchment hydrology (e.g., natural patterns of rainfall and snow melt runoff, influences of water management on timing of peak flows), the designer can estimate the frequency of events producing erosion or deposition in the channel or on the floodplain.

Fluvial energy can be used to laterally reconnect the stream with its floodplain and to longitudinally reconnect upstream transport reaches to downstream depositional zones. To address longitudinal connectivity, the designer should look for blockages or modified flow paths outside the defined project area along mainstem and tributary stream paths. Sometimes, upstream culvert or road crossing upgrades are integral to restoring fluvial connectivity and ensuring the success of a downstream floodplain restoration project.

Aside from stream energy, process-based restoration also harnesses biological energy, especially in alluvial stream reaches where vegetation tends to shape and direct the geomorphic and hydrologic processes (Castro and Thorne 2019). As degraded streams recover, ecological processes influence hydrogeomorphic process and vice versa leading to feedbacks between the two (Bendix and Stella 2013). Sometimes, in highly degraded systems, supplemental planting of diverse, locally appropriate vegetation may jumpstart a greater range of plant taxa.

Ecosystem engineers such as beavers, wolves, freshwater mussels, and willows were once more prevalent in these systems and affected structural complexity, flow paths, and channel stability (Pollock et al. 2007, Wolf et al. 2007, Lanman et al. 2013). Restoration actions that protect, work with, or encourage recolonization of such organisms can make use of biological energy to increase habitat diversity and resilience to maximize the benefits of restoration (Silverman et al. 2018). For example, a newly recovering depositional reach may develop channel bars, and if they are colonized by fast-growing willows and other plants, the bars can quickly stabilize and expand, potentially creating habitat for additional ecosystem engineers such as beavers that are known to increase habitat complexity, floodplain connectivity, and biodiversity (Pollock et al. 2014). Restored rates of primary production and more diverse producer communities are critical to recover biological components of the stream evolution process (Castro and Thorne 2019). These processes will influence food availability, competition for food, predation, and the production of target species (Benjamin et al. 2018). Biological and hydrological energy direct the biophysical recovery of the ecosystem and underscore the importance of expanding beyond traditional hydraulic energy and geomorphic form considerations when planning restoration projects.

Other important energy sources that merit evaluation include stochastic disturbances such as wildfire and landslides. Although we often think of process-based restoration in terms of moderate annual change, being prepared to capitalize on major disturbance events that deliver large pulses of sediment and wood can change a potential disaster into a restoration action. For example, after a large wildfire burns through a watershed, installing wood jams in low-gradient stream reaches to capture erosional runoff can quickly fill sections of incised channels instead of downstream reservoirs.

The energy design criterion discourages the use of external energy sources such as fossil fuels, needed to drive heavy equipment to implement conventional channel or floodplain reconstruction projects. Heavy machinery, however, may be necessary to make modifications to infrastructure (e.g., levee removal, road crossing repair) or for important infrastructure protection. By reserving heavy equipment primarily for infrastructure removal work, the risk of developing unsustainable habitat form through channel design and construction is minimized (Biron et al. 2014). In addition, existing recovery processes may be spared from unnecessary soil compaction, disruption of native seed banks, and creation of habitat favorable to invasive species (Palmer et al. 2014a, Gann et al. 2019).

Materials criterion: Projects use geomorphically appropriate materials to encourage channel evolution and avoid overly stabilizing project elements. The design criterion for materials requires they be locally sourced to direct fluvial and biological energy and reduce reliance on extrinsic sources of energy needed to bring outside materials to a site. Native materials also ensure that largely immobile structures are not built where such structures would not normally exist and where they may affect natural recovery processes. Instream structures built from wood, sod, and in some cases rock are used to maneuver water, sediment, and vegetative growth to nudge the system and prompt recovery through small, strategic interventions (Downs and Gregory 2004). Such structures help compensate for past alterations that were aimed at consolidating flows and facilitating water transport to accommodate agriculture, roads and bridges, and waterway commerce (Schoof 1980). Materials are strategically placed to accelerate channel evolution from single to multithread forms by expanding and accelerating aggradation, channel widening or partitioning channel stress, and creating new surfaces for vegetation growth and succession (Powell 1998, Manga and Kirshner 2000, Cluer and Thorne 2013, Pollock et al. 2014).

Structures made from locally sourced materials are used as short-term tools to accelerate beneficial biogeomorphic processes and are not necessarily expected to persist unmaintained through extensive winter flood flows (Staentzel et al. 2019, Wheaton et al. 2019, Williams et al. 2020). Structure failure can cause local erosion but does not inhibit natural channel dynamics and can be easily repaired or improved on in successive years until a self-sustaining recovery trajectory is reached (Pollock et al. 2014). In contrast, installing permanent structures, such as boulder-based grade control or bank protection in otherwise fine-textured channel–floodplain systems, can inhibit fluvial ecosystem development. Structures are evaluated on the basis of the process they induce and not their permanence.

Readily available locally sourced material reduces up-front design planning and construction allowing for more rapid implementation over larger stream segments at reduced cost. Beaver dam analogs (BDAs) and hand-placed wood jams described as “low-tech process-based restoration” exemplify process-based structures that are low cost, require minimal energy input, have minimal construction footprints, and allow for adaptive control of flow energy and sediment over time (Pollock et al. 2014, 2017, Wheaton et al. 2019).

Time criterion: Achieve habitat objectives over time via restored geomorphic and biologic processes. Including the criterion of time in the design process challenges the assumption that a project, once constructed, will function as intended without further need for management or adjustments. This criterion explicitly recognizes that time is required for the interaction of physical and biological processes to create naturally functioning fluvial ecosystems (Bergen et al. 2001). Minimally intrusive but incremental restoration over time promotes understanding of the system and helps to identify actions most likely to restore natural fluvial and biological processes that will eventually not require ongoing maintenance (Moore and Rutherford 2017). Although project designers often assume projects will function as planned in the years after construction, reassessments of restoration projects mostly showed otherwise (Bernhardt and Palmer et al. 2010, Moreno-Mateos et al. 2012, Pope et al. 2015, Moore and Rutherford 2017). The time criterion is necessary to avoid expectations of instant, one and done restoration, which can lead decision makers toward expensive projects with limited ecological benefit.

The inclusion of the time criterion forces the designer to anticipate how the project area will likely change over time in response to disturbances and ecosystem changes, such as floods, droughts, beaver dams and fires. For example, large floods can substantively affect sediment transport, deposition, and erosional processes, but such floods occur sporadically. Therefore, performance evaluations may require a decade or more to assess project success (Kondolf and Micheli 1995), although measurable improvements can be observed within shorter time frames (Wohl et al. 2019 and the Doty Ravine Creek example in the present article). The time frame for process-based restoration projects to achieve success will be determined in part by the extent to which source problems are addressed and adequate flows and other disturbance events occur. For example, an assessment of Deer Creek, Tehama County, California, showed that about eight 5-year flood events were likely needed for flows to rearrange the channel to resemble its complex natural state prior to flood-control interventions that simplified and straightened the stream, implying that the system would take about four decades to recover (Kondolf 2012).

In a process-based restoration project, it is equally important to measure whether the system is recovering as it is to determine whether it has recovered. Monitoring stream characteristics associated with stream evolution stages provides a means to track fluvial ecosystem recovery. Indicators include total stream length, number of confluence nodes and stream channels, number of vegetated islands, and extent of permanently flooded or raised water table area. An increase in these values over time indicates recovery toward increased ecosystem complexity and functionality (Cluer and Thorne 2013).

We propose that expected time frames for system recovery allow time for the likely occurrence of floods capable of doing geomorphic work, followed by periods of vegetative growth and other biological activity, such as beaver dam construction and recolonization of extirpated species. This suggestion parallels the concept of event-based monitoring, in which the occurrence of flows exceeding a given threshold trigger resurveys or evaluations of ecosystem response to restoration project actions, both immediately after the disturbance and following a period of postdisturbance recovery (Kondolf and Micheli 1995). Floods should generate measurable improvements, provide critical feedback, and create opportunities for adaptive management. This contrasts with conventional restoration approaches designed to resist the erosive activity of floods, whereby postflood monitoring is used to determine whether the designed form remained intact or whether heavy machinery is required for reconstruction.

Application of process-based design criteria: Doty Ravine restoration

We applied the process-based design criteria to a stream restoration project in the Doty Ravine Creek Basin (62 square kilometers), in the foothills of the Sierra Nevada of California. The project site consists of a 26-hectare (ha) floodplain along a 1.6-kilometer stream reach. In 2010, the site was acquired by the Placer Land Trust and subsequently managed for conservation purposes and cattle grazing.

The initial restoration activities between 2010 and 2015 did not follow process-based design criteria. During this period, about $160,000 was spent to construct an isolated 0.2 ha floodplain wetland, plant 10 ha of native trees and grasses on the floodplain, control beaver populations, and install livestock fencing to protect the narrow and straightened riparian corridor. By 2015, following this initial restoration effort, the floodplain remained dry during summer baseflows and was vegetated primarily with nonnative annual grasses, yellow star thistle (*Centaurea solstitialis*), and Himalayan blackberry (*Rubus armeniacus*). In 2016, the project partners undertook a new restoration plan that employed the space, energy, materials, and time design criteria (table 2).

Application of the process space criterion. We define four steps in applying the process space criterion, as follows.

First, define the predisturbance process space. The predisturbance floodplain, alluvial fans and tributaries were mapped using aerial imagery, topographic data, LiDAR, soil surveys, and field reconnaissance (figures 3 and 6). We identified hillslopes, tributaries, and channel banks as sources of sediment or wood and the disconnected floodplain as the new surface to receive these materials.

Next, define disconnected process space. We then delineated anthropogenic alterations that disconnected the floodplain from the channel and prevented floodwaters from exerting energy onto the disconnected process space. Major disconnections at Doty Ravine included 130-year-old levees and channel incision that concentrated stream energy within the narrow channel even at high flows. Heavy livestock grazing had denuded the floodplain and altered the potential interplay between stream energy, sediment, and vegetation. Once these disconnections and major land uses were mapped, we estimated the current or initial project process space. The historical, now-disconnected process space (26 ha) far exceeded the currently active, narrow stream corridor (3 ha; figure 2).

Prioritize process space reconnections. Our third step was to assess the ramifications of each identified impediment to process space and to prioritize feasible actions to maximize reconnection of disconnected process space. We identified strategic levee removal coupled with increased in-stream complexity via beaver dams and BDAs as having the greatest potential to reconnect large areas of the floodplain. We also assessed the potential to improve longitudinal connectivity at road crossings to increase downstream transfer of sediment and wood and removal of a water control structure disconnecting a tributary. Finally, we determined that a reduction in livestock grazing pressure was necessary to recover floodplain vegetation.

Finally, estimate final project process space. Once we identified high-priority actions to reclaim as much predisturbance process space as possible, we conducted a cost–benefit analysis and stakeholder outreach to determine how much could be done given the limitations of the project.

Table 2. Evaluation of the process-based restoration efforts at Doty Ravine, Placer County, California.

Criteria	Preproject condition	Goal	Outcome (4 years after project initiation)
Space	Flows confined laterally to 3 hectares (ha) of stream channel and longitudinal connectivity to tributary disconnected	Reconnect 19.5 ha (75%) of predisturbance lateral floodplain space and 300 meters (m) of longitudinal connectivity to tributary.	Gained 23 ha (88%) of lateral process space and 300 m longitudinal connectivity.
Energy	Levees contain stream in single-thread channel. Water control structure disconnects tributary.	Remove levees in strategic locations using an excavator. Remove water control structure with excavator.	Removed 150 cubic meters of levee material to open lateral and longitudinal connectivity (20 days at 320 liters of diesel fuel per day equates to approximately 115,200 megajoules).
	Confined stream energy incising channel and transporting sediment downstream.	Use stream energy to restore multi-thread channel form.	1300 m of new channel formed and 3820 cubic meters of sediment deposited (four peak flow events equate to approximately 625,615 megajoules).
	Narrow band of riparian vegetation (3 ha) along channel with upland annual grassland and shrubland on historical floodplain.	Encourage wetland plant growth following floodplain reconnection using solar energy and cattle exclosure.	Gained 23 ha of wetland riparian vegetation.
Materials	Minimal wood in channel resulting in reduced geomorphic complexity and habitat value for fishes and other aquatic organisms.	Build beaver dam analogues (BDAs) using imported posts and locally sourced weave materials to increase hydrological diversity and reconnect the floodplain.	Built 9 BDAs (2 people at 4 days per year for 4 years). Caused increased meanders in main channel, stream aggradation behind BDAs and floodplain reconnection.
	Beaver depredated by contracted pest control company to keep stream channel free of dams.	End beaver depredation practice onsite.	Five dams and a lodge built within the project area.
Time	Static stream channel and disconnected floodplain regardless of annual stream flows.	Over 10 years, restore a dynamic depositional multi-thread (stage 0) stream system with an active, productive floodplain.	Goal met in 4 years. Resulted in productive habitat for juvenile fishes, river otters, beaver, and wetland and riparian birds.

Note: The 62-square-kilometer catchment area includes a 1.6-kilometer stream reach and 26-ha floodplain and is owned by the Placer Land Trust.

The landowner was amenable to process-based restoration actions to reconnect the stream and floodplain on their property, but neighbors did not want floodplain reconnection. Road infrastructure modification was deemed infeasible within the near term (at least 10 years) and the upstream bridge did not appear to disrupt water flow, wood, and sediment transfer to a degree that would significantly limit site processes. Cattle grazing would remain on portions of the floodplain. Even with these limitations, we determined that we could regain most of the historical process space of the floodplain (23 of 26 ha) and restore longitudinal connectivity to 300 meters of a tributary stream via removal of the water control structure. We also suggested specific restoration actions to maximize floodplain connectivity including levee breaching, modifying grazing operations on the floodplain, adding BDAs to the incised channel, and stopping beaver depredation.

Application of the energy and materials criteria. We minimized input of external energy by using heavy equipment only to remove the infrastructure determined to inhibit natural processes. These included portions of the levee and the water control structure. Initial restoration actions in 2014 included ceasing beaver depredation and reducing cattle grazing of riparian areas. We observed the interaction of flow patterns and beaver dams in the incised channel and in the summer of 2016, we manually added wooden posts to increase their ability to withstand flood flows and allow beaver to focus their energy on building new dams and expanding habitat (Pollock et al. 2014). We also constructed nine BDAs with wood posts (more than 15 centimeters [cm] in diameter), small trees (less than 25 cm diameter), and willow branches to accelerate depositional processes and encourage channel aggradation, widening, and flow onto the floodplain. Some BDAs were placed in locations already showing evidence of deposition to promote further aggradation, whereas others were placed to direct flows into a targeted bank to increase meanders, recruit trees from the bank into the channel and release sediment for deposition downstream.

The in-channel beaver dams and BDAs quickly pooled water and increased water table elevations, instigating increased vegetation growth and side channel development over a portion of the previously disconnected process space. Water was now available to riparian vegetation throughout most of the valley bottom. This combined with cattle management practices increased the area of riparian vegetation growth from 3 to 23 ha. The aggrading stream channel and construction of dams by beaver increased the duration of hydric conditions on the floodplain even during the dry and typically least productive months (July through October; figure 3).

In 2017, a high flow of 21 m^3 per second (return interval about 2 years) deposited about 2450 m^3 of sand and gravel in the incised channel and floodplain and further reconnected the channel to the floodplain. Material retention was aided by beaver dams, BDAs, and the riparian vegetation

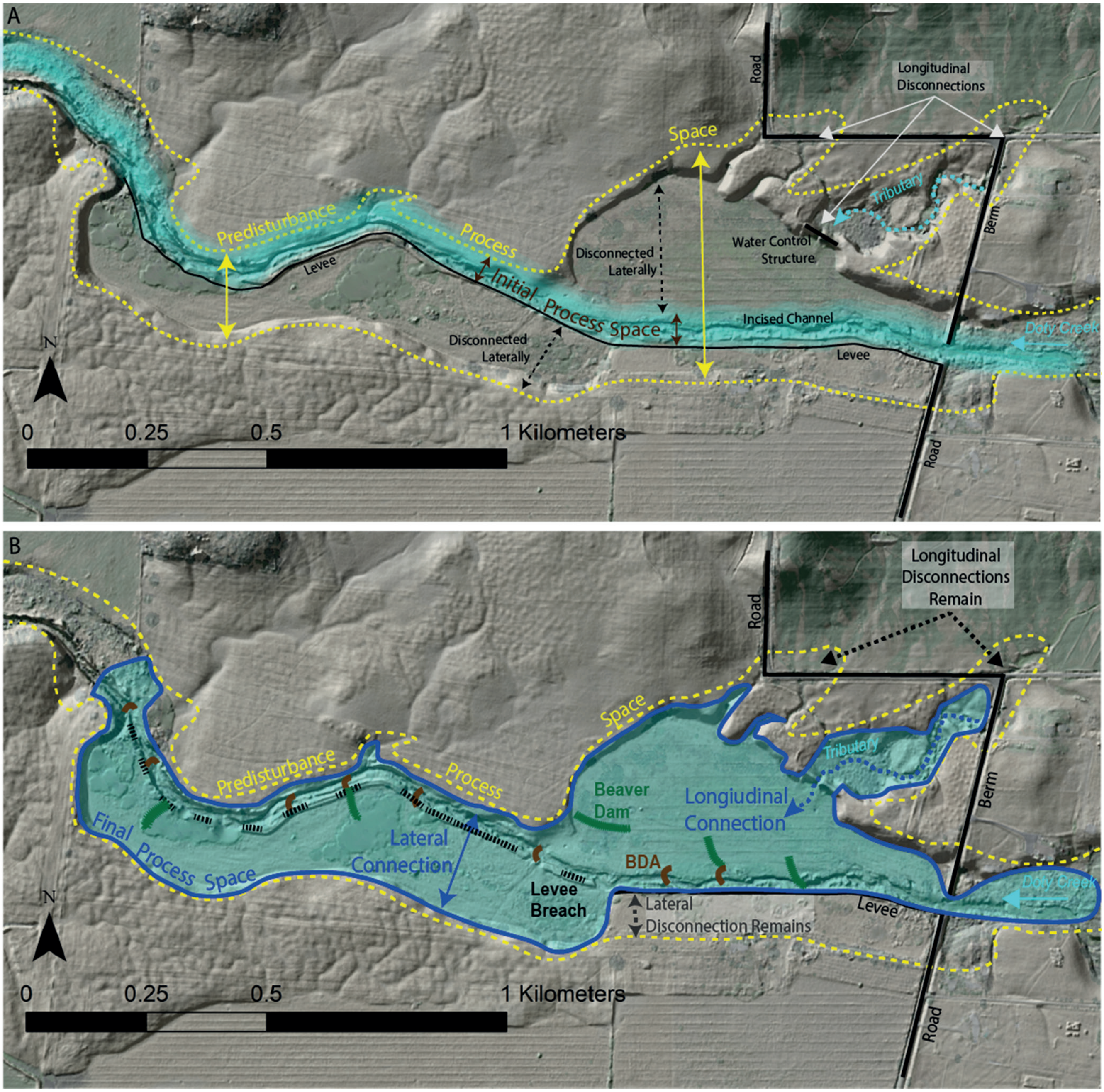

Figure 6. Process space limits are delineated for the Doty Ravine Creek Project to show (a) the total predisturbance space (outlined in yellow dashed line), prerestoration disconnected space, initially fluvially active space (highlighted blue), and (b) postrestoration final space (highlighted blue). Restoration actions that meet the space criteria result in a gain in process space for a project. This requires removing anthropogenic constrictions or modifying management to reconnect the floodplain (e.g., breach levees, repair road culverts, aggrade incised channel, beaver dam analogues (BDA) and control riparian grazing).

they stimulated throughout the floodplain over the previous year. If this volume of sand and gravel were imported from external sources, the cost would have been about $60,000, not including permitting and design. Follow-up flow events continued to deposit sediment on the floodplain and within the rapidly aggrading main channel. By 2019, the incised channel had three depositional zones established that no longer required maintenance of BDAs. Not all BDAs however were successful as three locations showed little to no signs of deposition during a 2–3-year period and beaver showed no interest in occupying them. Prior to restoration, the stream transported sediment, wood, and the associated minerals and nutrients directly through the reach. With the restoration depositional floodplains were returned and

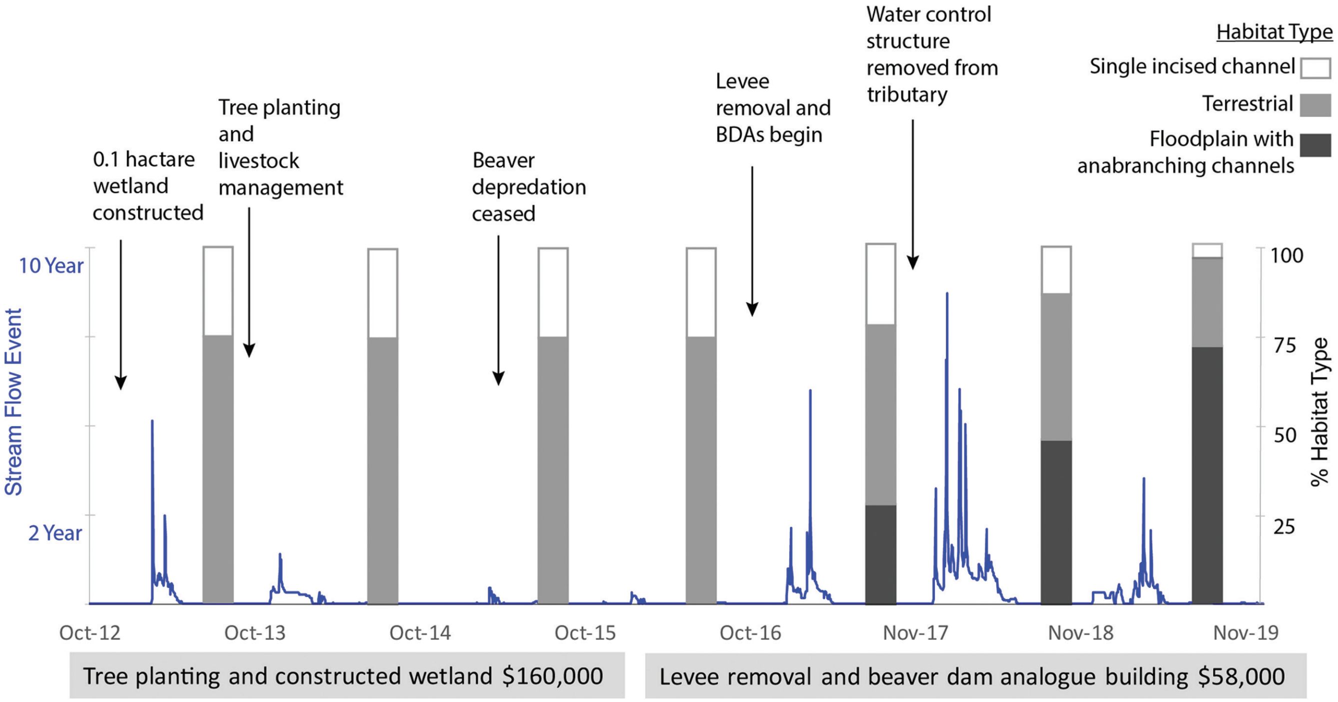

Figure 7. Assessment of restoration actions for the Doty Ravine project by observing habitat change along the hydrograph from October 2012 to November 2019. Initial restoration attempts (wetland construction and irrigated tree planting) were costly and did not restore fluvial process. Later, process-based restoration actions resulted in dynamic changes in habitat as the floodplain evolved from oak savannah to a wetland and anabranching channel complex.

retention of materials, resulted in rapid biological growth and productivity.

Application of the time criterion. We initially estimated floodplain reconnection using process-based restoration would require about 10 years. This was based on characterization of existing recovery processes and the flow regime. For example, we observed small depositional zones forming behind existing beaver dams but thought they would take many years to aggrade because they frequently blew out during high flows. The project was also started during a multiyear drought (2014–2016) so we were observing very little sediment transport and the lack of riparian vegetation on the floodplain meant surface roughness would remain low and materials available for beaver activity would be limited. However, the 2017 high-flow event coupled with the beaver dams and BDAs to capitalize on it resulted in recovered hydrology and regeneration of riparian vegetation within 3 years (figure 7).

By summer 2019, most of the project process space changed from terrestrial habitat to wetlands. Stream channel length and confluence nodes increased as beaver constructed small dams laterally across the floodplain adding to the complexity of flow paths. Total stream length increased from 725 to 1800 meters, confluence nodes increased from 3 to 13, and the number of islands increased from 4 to 12.

Quantifying these changes became difficult because of the complexity of multiple shallow channels that readily overflowed onto the floodplain. In 5 years, process-based actions increased the aerial extent of dynamic fluvial habitat from approximately 3 to 23 ha of floodplain. In this time, project costs totaled $58,000 ($2500 per ha), including the cost of off-site transport of levee material.

Conclusions

The translation of process-based restoration principles and standards into on-the-ground implementation has proven challenging. Process-based restoration requires design criteria that guide a project to address source problems in the system (e.g., disconnectivity and land management), so nature can do the work of rebuilding habitat. The design criteria we presented may be used to evaluate whether proposed stream and river management actions are effective for meeting process-based restoration objectives (figure 8). For example, infrastructure improvements may provide considerable restoration benefits when they provide greater space for fluvial processes. The criteria may also inform stream projects aimed at greenhouse gas offsets where emissions during implementation affect the overall carbon balance sheet.

The Doty Ravine Creek floodplain example highlights that opening space and increasing connectivity using site energy and natural materials can result in considerable increases in habitat complexity, as well as restored dynamism throughout

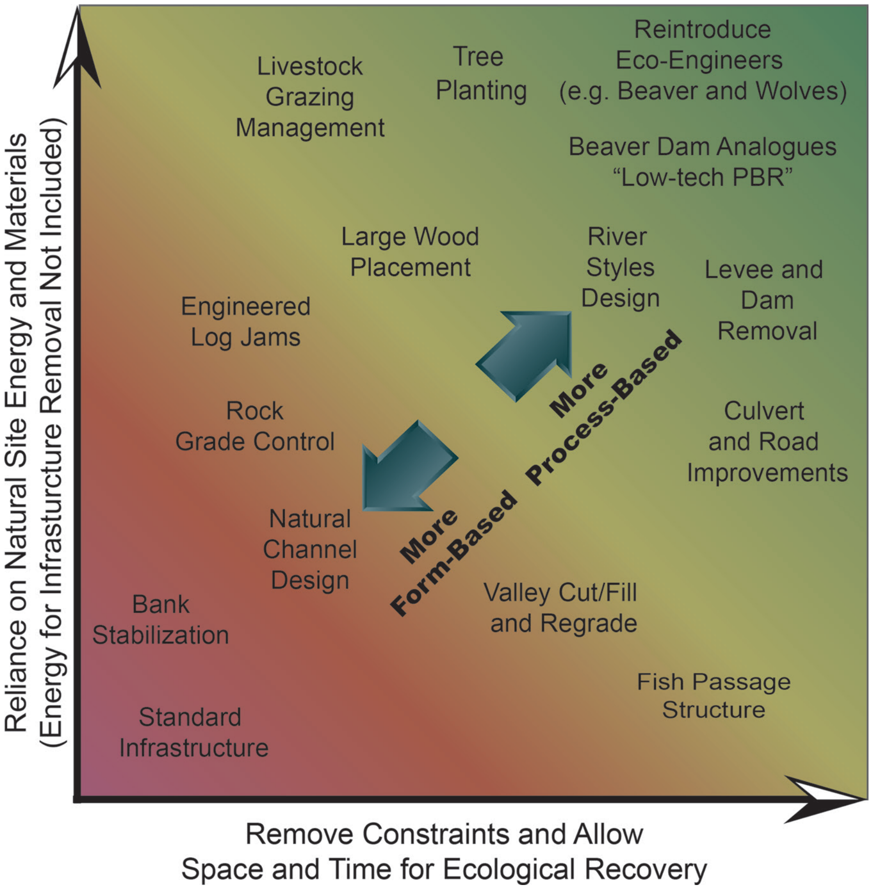

Figure 8. Conceptual diagram evaluating the relative potential for river management actions to meet process-based restoration objectives. Process-based actions are those that rely on energy and materials of the site and that achieve high levels of connectivity and allow for sufficient time and space for natural processes to restructure and recover habitat complexity.

a valley bottom in just a few years. These design criteria supported an overarching project goal of a dynamic ecological endpoint and did not lead designers to seek deterministic outcomes in the specific types or arrangement of habitat. Even though stochasticity was inherent in the design, progress was clearly measured using biological and geomorphic performance metrics to track the self-healing capacity of the system and inform adaptive management.

Similar design approaches and outcomes were observed in Maggie Creek, in Nevada, and Bridge Creek, in Oregon, where significant aquatic habitat complexity was achieved in alluvial stream reaches by removing constraints such as cattle grazing and working with beaver or installing wood structure (Bouwes et al. 2016, Silverman et al. 2018). Even in highly altered ecosystems land uses accommodate "accidental" urban wetlands that provide more services, such as nutrient or carbon sequestration than their constructed wetland counterparts, and at a reduced cost and regulatory burden (Palta et al. 2017).

In systems in which overwhelming source problems cannot be addressed, such as directly downstream of major dams that greatly reduce high flows and trap sediment, the stream energy and sediment supply may be too low to meet recovery objectives. The degree to which restoration actions resolve source problems that hold the stream network in a degraded state often determines the potential to which natural process may be used for stream restoration. In the Doty Ravine Creek example, sections of degraded incised channel remained in 2019 but had little influence on the ecosystem's ability to create and maintain higher levels of complex and multithread channels and wetlands. This has important implications to stream restoration design suggesting that eliminating, reconstructing or filling undesirable stream channel forms may be unnecessary for meeting stream and floodplain restoration goals.

We hope that these design criteria aid in the transfer of stream restoration science and research into practice. As such they should evolve, change, and grow with the developing discipline. Shifting the design process from a focus on constructed habitat to addressing ecosystem problems at the source should ultimately result in more sustainable projects and increase the probability that restoration is conducted at the large spatial scales needed to improve long-term ecosystem sustainability.

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