Supplement S1 of *International principles and standards for the practice of ecological restoration. Second edition, 2019.*

Historical principles and concepts of ecological restoration and allied activities

Since the early 1980s (e.g., Bradshaw 1983), numerous publications have considered principles and concepts that set the aspirational context for restoration or provide guidance for practice. Recent publications have proposed that restoration should be Effective, Efficient, Engaging, and Sustainable (e.g., Keenleyside et al. 2012; Suding et al. 2015), and these categories can be used to organize these historical ideas. *Effective* ecological restoration re-establishes and maintains ecological and social values. *Efficient* ecological restoration maximizes beneficial outcomes while minimizing costs in time, resources, and effort. *Engaging* ecological restoration collaborates with partners and stakeholders, promotes participation, and enhances experience. *Sustainable* ecological restoration ensures the ecological, technical, and social ingredients are in place to achieve long-term security of restored sites. The four categories are used below as a structure to organize a longer list of detailed principles and concepts derived from many documents relating to restoration principles over recent decades. These historical principles have contributed substantially to the synthesis of the eight Principles (Table 1) and to the development of the Standards of Practice in the SER Standards.

1. Effective Ecological Restoration

1.1 Complements the conservation of native ecosystems through increasing the integrity and area of resilient native ecosystems. The world's relatively intact land and water ecosystems represent an invaluable natural heritage that is under threat and requires urgent conservation (Hobbs & Norton 1996; USEPA 2000; Clewell & Aronson 2013; Cairns 2014, CBD 2016). Restoration focuses on returning the structure, function, composition, connectivity, and dynamic processes of native ecosystems, including their natural capital for the provision of ecosystem services (Aronson et al. 1993; DellaSala et al. 2003; SER 2004; Gann & Lamb 2006; Parks Canada 2008; Keenleyside et al. 2012; Clewell & Aronson 2013; Cairns 2014; Suding et al. 2015; CBD 2016; Brancalion & Chazdon 2017; Viani et al. 2017; Besseau et al. 2018). It complements a larger suite of allied activities to collectively improve the functioning of global ecosystems and the ecosystem services they provide (SER 2004; Clewell & Aronson 2013; CBD 2016; Aronson et al. 2017).

1.2 Is aspirational in terms of quality and quantity of outcomes. The ethic of ecological restoration is to encourage authentic ecological recovery to the highest quality and scale feasible in each circumstance, even if that outcome can only be realized over long time frames (SER 2004, Clewell & Aronson 2013, Besseau et al. 2018).

1.3 Is universally applicable and practiced locally with positive regional and global implications. Restoration is inclusive of aquatic and terrestrial ecosystems, with local actions having regional and global benefits for nature and people (SER 2004; Gann & Lamb 2006; Clewell & Aronson 2013; Suding et al. 2015; CBD 2016; Besseau et al. 2018).

1.4 Reflects human values while recognizing nature's intrinsic values. Ecological restoration is undertaken for many reasons including economic, ecological, cultural, and spiritual values (Besseau et al. 2018). Values also drive people to seek to repair and manage ecosystems for their intrinsic value, rather than for the benefit of humans alone. In practicing ecological restoration, a more ethical and satisfying relationship between humans and the rest of nature is sought (Higgs 1997, SER 2004, Parks Canada 2008, Clewell & Aronson 2013, Suding et al. 2015).

1.5 Addresses causes to the extent possible and at the most appropriate scales. The anthropogenic threats causing degradation need to be addressed or mitigated, and at the various scales at which they occur, if restoration interventions are to be effective in the long term (USEPA 2000; Hobbs & Norton 2004; Clewell & Aronson 2013; Rieger et al. 2014; CBD 2016; Besseau et al. 2018).

2. Efficient Ecological Restoration

2.1 Initiates and supports a process of recovery carried out by the organisms themselves. Re-assembling species and habitat features on a site invariably provides just the starting point for ecological recovery; the longer-term process is performed by the organisms themselves (DellaSala et al. 2003; SER 2004; Clewell & Aronson 2013). The speed of this process can sometimes be increased with greater levels of financial resourcing (Bradshaw 1983).

2.2 Accounts for the broadscale context and prioritizes resilient areas. Sites must be considered in their broader geographical context to adequately assess complex threats and opportunities (Hobbs & Norton 1996, USEPA 2000, Keenleyside et al. 2012). Increased ecological and economic efficiency results from improving and coalescing larger and better condition patches and progressively doing this at increasingly larger scales. Geographic location in the landscape/aquatic environment and degree of degradation will influence the sequence and scale of investment required (USEPA 2000; DellaSala et al. 2003; Conservation Measures Partnership 2013; Besseau et al. 2018).

2.3 Applies approaches best suited to the degree of impairment. Many areas retain some capacity to naturally regenerate given appropriate interventions; whereas highly damaged areas might need a reconstruction approach to overcome barriers to recovery (Aronson et al. 1993; Hobbs & Norton 1996; McDonald 2000; Cairns 2014). The inherent resilience of the species remaining on a site must be considered prior to identifying required interventions (SER 2004; McDonald 2000; USEPA 2000; Clewell & Aronson 2013).

2.4 Addresses all biotic components. Restoration seeks to recover complex biota at all levels from micro- to macro-organisms. This is particularly important to ensure the reinstatement of plant-animal interactions and trophic complexity required for well-functioning ecosystems (SER 2004; Clewell & Aronson 2013). Genetically informed propagule sourcing and population design can be critical to ensuring reproductive ecosystems, particularly to allow potential for species in fragmented ecosystems to adapt in a changing climate (McDonald et al. 2016).

2.5 Draws rigorous, relevant, and applicable knowledge from a dynamic interaction between science and practice. All forms of knowledge, including that gained from science, nature-based cultures, and restoration practice, are important for designing, implementing, and monitoring restoration projects and programs (Bradshaw 1983; Aronson et al. 1993; Hobbs & Norton 1996; Gann &

Lamb 2006; Parks Canada 2008; Clewell 2009; Keenleyside et al. 2012; CBD 2016; Viani et al. 2017; Liu et al. 2019). Results of practice can be used to refine science and science used to refine practice (Bradshaw 1983; Jordan et al. 1987; Hobbs & Norton 1996), particularly when standardized monitoring procedures are used (Viani et al. 2017).

2.6 Is improved by a workforce knowledgeable about local ecosystems and their history. Improved outcomes can increase with an engaged workforce with knowledge of (1) the target ecosystem's biota and abiotic conditions and how they establish, function, interact, and reproduce under various conditions including anticipated climate change; and (2) responses of these species to specific restoration interventions tried elsewhere (Bradshaw 1983; DellaSala et al. 2003; Cairns 2014). Many projects require multi-disciplinary teams (USEPA 2000).

2.7 Takes an adaptive management approach. Ecosystems are often highly dynamic, particularly at early stages of recovery and each site is different. Appropriate solutions will be necessary for specific ecosystems and locations, and these solutions may only come through building appropriate levels of monitoring (and, in some cases, more formal experimentation) into the project to inform adjustments during its implementation phase (Jordan et al. 1987; USEPA 2000; Clewell & Aronson 2013; Cairns 2014; Temperton et al. 2014; Viani et al. 2017).

2.8 Requires systematic site assessment and planning to identify reference ecosystems, and to develop clear and measurable targets, goals, and objectives. Site assessment will lead to the identification of a reference ecosystem (SER 2004; Palmer et al. 2005; Clewell & Aronson 2013; Suding et al. 2015; Aronson et al. 2017). To measure progress, an approach for assessing restoration outcomes should be identified early and address the range of ecosystem attributes considered (Aronson et al. 1993; SER 2004; Clewell 2009; Viani et al. 2017). This will ensure that a project collects site-relevant information for monitoring, and better attune the planning process to devise strategies and actions more likely be successful (USEPA 2000; DellaSala et al. 2003; SER 2004; Keenleyside et al. 2012; Clewell & Aronson 2013; Cairns 2014; Rieger et al. 2014; Viani et al. 2017).

2.9 Is adequately resourced. Budgeting strategies must be identified at the outset of a project and funding secured for planning, monitoring, and implementation (DellaSala et al. 2003; Palmer et al. 2005; Rieger et al. 2014). Larger budgets may allow restoration activities to be conducted over shorter periods, but smaller budgets applied over longer time frames can be highly effective. Well-supported community volunteers can play a valuable role in improving outcomes when budgets are limited (Clewell & Aronson 2013; Rieger et al. 2014).

2.10 Takes advantage of economic incentives and efficiencies offered by partnerships and multi-benefit projects. Restoration can gain efficiencies from government-initiated policies and by integration into other projects funded through gains projected to flow from repaired natural capital (DellaSala et al. 2003; Parks Canada 2008; Clewell & Aronson 2013; Besseau et al. 2018).

3. Engaging Ecological Restoration

3.1 Provides opportunities for benefits to flow to communities, particularly for reinforcement of nature-based culture. Restoration can provide a suite of ecosystem services that enhance human quality of life

(Cairns 1995; Higgs 1997; SER 2004; Gann & Lamb 2006; Keenleyside et al. 2012; Clewell & Aronson 2013; Temperton et al. 2014; Suding et al. 2015; CBD 2016; Brancalion & Chazdon 2017; Viani et al. 2017; Besseau et al. 2018). The process of restoration can bring individuals and communities together in transforming ways, particularly when the rights of Indigenous Peoples and local communities are respected (REDD+ SES 2012; CBD 2016) . This can benefit those involved by improving physical and mental wellbeing, providing a sense of place and belonging, increasing social bonding, and generating employment opportunities (SER 2004; Gann & Lamb 2006; Parks Canada 2008; Keenleyside et al. 2012; Clewell & Aronson 2013; CBD 2016).

3.2 Recognizes the importance of community and individual relationships to the health and security of native ecosystems. Restoration projects that tap into existing positive relationships between people and native ecosystems can improve their knowledge of ecosystems (Cairns 1995; Higgs 1997; DellaSala et al. 2003; Gann & Lamb 2006; Keenleyside et al. 2012; Clewell & Aronson 2013; Temperton et al. 2014; Suding et al. 2015; CBD 2016; Besseau et al. 2018) and reinforce the positive roles people can play in healing ecosystems and maintaining ecological processes (Parks Canada 2008; Keenleyside et al. 2012; CBD 2016).

3.3 Establishes effective communication and outreach with stakeholders. Outcomes of restoration projects are improved when there is genuine consultation and engagement with stakeholders including local communities, particularly traditional and Indigenous communities. Communication and outreach is best achieved by involvement at the planning stage and should continue throughout the project (Cairns 1995; Higgs 1997; USEPA 2000; Gann & Lamb 2006; Parks Canada 2008; Keenleyside et al. 2012; Clewell & Aronson 2013; CBD 2016; Viani et al. 2017; Besseau et al. 2018).

3.4 Involves stakeholders in the development of solutions. Ecological restoration outcomes are often more effective and efficient if stakeholders are engaged in assessing problems and devising solutions. Restoration outcomes are more secure when appreciable benefits or incentives are available to stakeholders and where stakeholders are themselves engaged in the restoration effort, building ownership into local cultures (Cairns 1995; Higgs 1997; Gann & Lamb 2006; Parks Canada 2008; Keenleyside et al. 2012; CBD 2016; Besseau et al. 2018).

4. Sustainable Ecological Restoration

4.1 Aims to establish systems that are self-sustaining and resilient. This requires matching the target ecosystem to environmental conditions (National Research Council 1992; USEPA 2000; Cairns 2014; Viani et al. 2017), by harnessing natural processes (DellaSala et al. 2003), and ensuring processes needed to monitor and maintain the ecosystem are put in place for the long term (Palmer et al. 2005; Keenleyside et al. 2012; Clewell & Aronson 2013; Viani et al. 2017).

4.2 Looks to the past and the future, building in adaptability. Understanding past conditions provides an anchor for reference ecosystems, but the goal is to ensure a dynamic ecosystem that adapts and changes with changing environmental conditions (USEPA 2000; SER 2004; Choi et al. 2008; Parks Canada 2008; Clewell 2009; Keenleyside et al. 2012; Clewell & Aronson 2013; Temperton et al. 2014; Suding et al. 2015; Rissman et al. 2018).

4.3 Is secured by adequate long-term management arrangements. Secured tenure, property owner commitment, and long-term management are necessary for most restored ecosystems, particularly where the causes of degradation cannot be fully addressed (Gann & Lamb 2006; Parks Canada 2008; Keenleyside et al. 2012; Clewell & Aronson 2013; Rieger et al. 2014; CBD 2016).

4.4. Recognizes a need for ongoing commitment. The decision to restore a site is best made collectively (SER 2004) to provide long-term security and ongoing activity on the part of partner agencies and stakeholder groups (Parks Canada 2008). This requires periodic revitalization of intergenerational interest through cultural engagement, ongoing communication, education, effective participation and a range of other strategies (SER 2004, Clewell & Aronson 2013; CBD 2016).

Table 1. Clusters of historical principles that have contributed to the synthesis of the eight principles highlighted in the SER standards.

PRINCIPLE IN SER STANDARDS	HISTORICAL PRINCIPLES DRAWN UPON (NUMBERS REFER TO THE LIST IN THIS APPENDIX)
ECOLOGICAL RESTORATION:	
1. Engages stakeholders	1.3; 1.4; 3.1; 3.2; 3.3; 3.4.
2. Draws on many types of knowledge	2.5; 2.6; 2.7; 3.3; 3.4.
3. Is informed by native reference ecosystems while considering environmental change	1.1; 1:4; 2.2; 2.4; 2.8; 4.1; 4.2.
4. Supports ecosystem recovery processes	1.1; 2.1; 2.2; 2.3; 2.6; 2.7; 4.1; 4.2.
5. Is assessed against clear goals and objectives using measurable indicators	1.5; 2.5; 2.6; 2.7; 2.8.
6. Seeks the highest level of recovery attainable	1.1; 1.2; 2.3; 2.9; 2.10; 4.1; 4.3; 4.4.
7. Gains cumulative value when applied at large scales	1.1; 1.2; 1.3; 1:5; 2.2; 2.10.
8. Is part of a continuum of restorative activities	1.1; 1.2; 1.3; 1.4; 1.5; 2:3; 2.10; 3.1; 3.2; 3.4.

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