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Cumulative Effects Assessment: Theoretical Underpinnings and Big Problems

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Abstract: Cumulative effects assessment (CEA) is a sub-discipline of environmental impact assessment that is concerned with appraising the collective effects of human activities and natural processes on the environment. Aspirations for CEA have been expressed by many authors since 1969, when the foundation of environmental appraisal was laid by the US National Environmental Policy Act. This paper's purposes are (1) to review aspirations for CEA, relative to current practice, and (2) to fully explain and critique the logic that connects CEA's operational steps and underlying philosophies. A literature review supports the following statements: Some conceptualizations emphasize the delivery of information to support decision making as the key purpose of CEA; others deem collaboration, debate, and learning as most important. Consensus on CEA's operational steps has been reached, but each step requires practitioners to make analytical decisions (e.g., about the scope of issues to include or the time horizon to consider) and objective rules for how to approach those decisions are lacking. Numerical methods for assessing cumulative effects are largely available, meaning that CEA's biggest problems are not scientific. CEA cannot succeed without substantive public engagement, monitoring and adaptive management. CEA is best undertaken regionally, rather than project-by-project. CEA and planning are complementary, and should be merged. In its most enlightened form, CEA is a useful tool for ensuring that human undertakings ultimately conform to Earth's finite biosphere, but current practice falls short of the ideal, and CEA's logical derivation is not entirely sound. As regards CEA's big problems, sustainability has not been defined clearly enough to make criteria for judging the significance of cumulative effects indisputable; legal, regulatory, and institutional frameworks are poorly aligned for CEA; and objective criteria for judging the adequacy of CEA's scope, scale, and thresholds don't exist, which makes the question of how to provide general guidance to practitioners intractable. Recommendations call for sustainability goals to be clearly expressed as measurable targets. Furthermore, precaution in human enterprise should be exercised by avoiding, minimizing, restoring, and offsetting negative cumulative effects. CEA can assist by quantifying and optimizing trade-offs.

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51 *conceptual model, precautionary principle*

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Introduction

Environmental Impact Assessment (EIA) is a process by which the outcomes of a project are identified, predicted, evaluated and (where necessary) mitigated before major decisions and commitments are made (Cashmore 2004, Glasson et al. 2013): a way to explore “options for more-sustainable (i.e., less environmentally damaging) futures” (Duinker and Grieg 2007). The EIA concept was introduced legislatively in the USA via the 1969 National Environmental Policy Act (Senate and House of Representatives of the USA 1969). By 1996, EIA had spread to more than 100 countries (Benson 2003), and by 2012, some form of EIA had been mandated in 191 of the World’s 193 nations (Morgan 2012, Pope et al. 2013).

Senécal et al. (1999) listed 4 objectives of EIA: to ensure that the environment is considered in the decision-making process surrounding new developments; to minimize or offset adverse effects; to protect ecological processes and functions; and to promote sustainability and optimal resource use. Gibson (2012) extended these objectives, by recommending that EIA should: apply to all potentially significant undertakings; give equal attention to “biophysical, social and economic considerations”; begin at the outset of the decision process; have clear requirements and a predictable process; focus “attention on the most significant undertakings”; expedite “public engagement and learning”; render the decision-making process more consistent, impartial, transparent, and accountable; mesh easily with extant regulatory, planning, or policy instruments; and provide an authoritative basis for enforcement, monitoring and adaptation.

Over time, EIA practice has been continually scrutinized, and has diversified into many distinct and specialized sub-disciplines (Pope et al. 2013, Morrison-Saunders et al. 2014). This diversification has

coincided with our growing acknowledgement of (and desire to better manage) the widespread influences that human activities have on the environment (Morgan 2012). This EIA scrutiny soon illustrated that planning, legal, policy, and regulatory processes were not considering the combined environmental effects of multiple human activities (Damman et al. 1995), and that the EIA process was failing to explicitly consider that “all effects are cumulative” (Duinker and Greig 2006; Gunn and Noble 2011). In particular, the common practice of assessing short-term effects, project by project, was deemed ineffective because it provided little scope for managing the effects of more than one project that may be occurring in an area (Brundtland 1987, Spaling et al. 2000, Connelly 2011). As a response to such criticism, cumulative effects assessment (CEA) was proposed as a way to evaluate the collective effects of actions on the environment (Seitz et al. 2011). Cumulative effects assessment promises to improve EIA by considering how a given “receptor is affected by the totality of plans, projects and activities, rather than on the effects of a particular plan or project” (Therivel and Ross 2007). CEA is considered to be a sub-discipline of EIA, because it derives from EIA’s principles, methods and tools, and is broadly applicable across the diversity of EIA practice (Baxter et al. 2001, Canter and Ross 2010, Bond and Pope 2012, Morrison-Saunders et al. 2014).

Case studies of CEA practice, critiques (e.g., Duinker and Greig 2006), and “lessons learned” (Canter and Ross 2010) are abundant in the published literature¹. Although some retrogression (i.e., return to a former, less effective state) of CEA practice has occurred (i.e., e.g., Gibson 2012), published articles have stimulated and documented a limited refinement of CEA over time (Canter and Ross 2010). The evolution of EIA thinking has been driven by practice (i.e., the need to satisfy legislative and regulatory requirements), not by theory (Cashmore 2004, Retief 2010), which remains inconsistent and

¹ For example, a relatively restrictive keyword search of Thomson-Reuters’ Web of Science, using the search term “(cumulative NEAR/1 effects) AND assessment” to query the “environmental science/ecology” and “sociology” research domains, returned 788 citations on 23 September 2015.

incomplete (Cashmore 2004, Judd et al. 2015). Despite its 45 year history, the discipline is still viewed as young and unproven (Bérubé 2007): a diverse and confusing assortment of methods (Cormier and Suter 2008, Seitz et al. 2011, Pope et al. 2013), uncoupled from theory (Lawrence 2000, Cashmore 2004). Illuminating the conceptual or theoretical basis for EIA and CEA, merging theory and practice (e.g., Pope et al. 2013), and establishing how performance is to be assessed (e.g., Retief 2010, Morgan 2012) is essential if we are to answer Senécal's (and co-authors'; 1999) call for EIA practice that is "purposive, rigorous, practical, relevant, cost-effective, efficient, focused, adaptive, participative, interdisciplinary, credible, integrated, transparent, and systematic". There is some urgency to these tasks, given the presently difficult economic times, in which governments seek to stimulate economic activity by encouraging development and cutting green tape (e.g., Bond and Pope 2012, Gibson 2012, Middle et al. 2013, Morrison-Saunders et al. 2014); and "the severity of many cumulative effects – global warming, plummeting world fish stocks, decline in biodiversity – means that we have to get (CEA) right, and fast." (Therivel and Ross (2007).

This paper explores aspirations for CEA that have been expressed by many authors at different times throughout CEA's history. Its purposes are to synthesize a formal understanding of what CEA is *supposed* to achieve, to explain how its components are conceptually linked together (i.e., as a "theory" or conceptual model²), to expose inconsistencies (both in CEA's underlying logic, and as incongruences between current practice and aspiration), and to recommend some pathways for improvement.

² As per Lawrence (2000), the terms *theory* and *model* are used to describe loosely affiliated conceptual themes.

Logical Connections among CEA’s Components

The following is intended as a comprehensive description of CEA, and an illustration of logical connections among its components. The description proceeds as a deductive argument (e.g., Michalos 1970), based on a series of premises (denoted P1 to P95) and conclusions (denoted C1 to C14). Conclusions build on one another, and each one is positioned in the sequence to immediately follow its full set of supporting premises. The format will appear unorthodox to scientific readers, but it highlights incomplete or inconsistent logic, and invites debate over problems and solutions.

P1: Earth’s biosphere and ecosystems provide the essentials for life, and enable our survival as a species (MEA 2003)³.

P2: Earth’s biosphere is finite, as are its ecosystems.

P3: As a foundation for human life and well-being, there is no substitute for Earth’s biosphere.

P4: Human undertakings influence Earth’s biosphere (and its ecosystems) in a variety of ways, and changes to the biosphere have occurred as a result of human activities (Vitousek et al. 1997, Wackernagel and Rees 1998, MEA 2005, Foley et al. 2005, Steffen et al. 2007, Rockström et al. 2009, Ellis 2011, Hegmann and Yarranton 2011).

P5: EIA and CEA began in the United States, as legislative requirements under the 1969 National Environmental Policy Act (Pope et al. 2013). Since 1969, CEA’s concepts and methodologies have been

³ Social, cultural, and economic attributes of the societies we live in do enhance our standard of living, but this can only happen after the basics for life (e.g., water, air, food) are provided by the biosphere.

developed, refined, and entrenched world-wide as laws, policies and regulations (Benson 2003, Pope et al. 2013); however CEA's evolution has not been linear, and setbacks have been documented (e.g., Gibson 2012).

C1: Human enterprise (e.g. land-use, economic growth) must conform to the limitations of Earth's biosphere (Boulding 1966, Daly 1977; Wackernagel and Ree's 1998, Schnaiberg and Gould 2000, Moldan et al. 2012) and CEA is an important tool for making this happen (e.g., Morgan 2012, Morrison-Saunders et al. 2014)

P6: Ecosystems have three domains: physical habitat, biota, and interactions between habitat and biota (Tansley 1935). Ecosystems are characterized by non-equilibrium and irreversible phenomena, and are open, complex, adaptive, hierarchical systems that are highly integrated by matter and energy flows (Hayha and Franzese 2014, Jorgensen et al. 2011).

P7: An *effect* is a change to the structure or function of the ecosystem (i.e., a change to the habit, biota, and/or their interactions).⁴ Effects may be measured against the normal range of variability (Kilgour et al. 1998, Scherer 2011) associated with a specified spatial and temporal baseline (Glasson et al. 1994,

⁴ One can argue that the definition of *effect* should be broadened, for example to include changes to social or economic factors, because of the many ways in which human and biophysical factors interact, and because social, economic, and environmental factors are equally considered in sustainability assessments; however one can also argue that, despite their political salience in the decision-making process, social and economic factors ultimately depend on the environment. The contemporary metaphor for sustainability is a series of nested bowls (e.g., Wikimedia Commons 2015), with the environment bowl containing society, and society containing the economy; it is no longer a 3-legged stool (e.g., Dawe and Ryan 2003) or triple bottom line (e.g., Elkington 1997). Regardless, laws and historical practice show that CEA is chiefly concerned with ecological effects, and as Sheate (2010) wrote, we should not lose sight of the environmental origins and purpose behind EIA (hence CEA) as an instrument for environmental advocacy.

Pavlickova and Vyskupova 2015); however deviation from a statistically defined normal range does not necessarily signify ecological significance.

P8: Effects can arise because of natural processes or because of “stressors”⁵ related to human activities.

P9: land-uses or environmental issues (e.g., urban development, agriculture) often implicate multiple stressors (Chapman and Maher 2014); that is, they cause environmental change by a variety of mechanisms.

P10: Effects accumulate (i.e., *become cumulative*) as repeated insults of a single stressor — i.e., when exposures to the stressor “take place so frequently in time or so densely in space that the effects of individual insults cannot be assimilated” (Damman et al. 1995, Pavlickova and Vyskupova 2015). They also accumulate via the interaction of multiple stressors (Smit and Spaling 1995), the nature of the interaction potentially varying over time or space.

P11: Cumulative effects can be enigmatic. They include individually minor but collectively significant changes that take place over a period of time (US-CEQ 1978, Cocklin et al. 1992, Therivel and Ross 2007); they include changes that may take place remotely from the location where the stressor is created; they include changes that may be undetectable by any specific monitoring method; they include secondary effects facilitated by, but not directly caused by, a given undertaking; and they include changes caused by interactions between multiple stressors and/or multiple undertakings (Raiter et al. 2014). They may be direct, indirect, antagonistic, synergistic, linear, or non-linear, and they may manifest following a complex chain of events (CEARC 1988, Scherer 2011).

⁵ A stressor is “any physical, chemical, or biological entity that can induce and adverse response” (US EPA 2000)

P12: Legislative, policy, and regulatory interpretations of cumulative effects vary, but they are approximately defined as ecosystem changes that result from the incremental, accumulating, and interacting impacts of an action when added to other past, present, and reasonably foreseeable future actions (e.g., US-CEQ 1978, Spaling et al. 2000, Dubé 2003).

C2: Cumulative effects⁶ are aggregated, collective, accruing, and/or combined ecosystem changes that result from a combination of human activities and natural processes (Scherer 2011); however they are commonly defined in a more restrictive sense in policies, laws, and regulations — for example, as effects of an undertaking and its interaction with other activities that occur at the same time and in the same area (e.g., EU 1985, Dammon et al. 1995).

P13: CEA is the assessment of ecosystem changes that accumulate from multiple stressors, both natural and manmade (Dubé et al 2013).

P14: CEA is a process by which the potential environmental effects of one or more alternate visions for a particular place, sector, or other entity are systematically assessed (Gunn and Noble 2009; Seitz et al. (2013).

P15: Cumulative effects assessment seeks to understand changes in environmental condition from past to present, and to predict potential outcomes associated with proposed developments (Dubé et al.

⁶ A hypothetical cumulative effects scenario: roads are built on unstable terrain during a time of above average rainfall. Landslides and avulsions in a local stream become more frequent, thus erosion is exacerbated and the stream channel is destabilized. Gravel beds used by fish during spawning are clogged with sediment, and after several years, populations of several fish species are outside of historical limits (adapted from Scherer 2011).

205 2013) and other foreseeable developments that may be subsequently induced. As is the case with EIA,
206 CEA's emphasis is on exploring the future (Rubin and Kaivo-oja 1999, Duinker and Grieg 2007).

207
208 **C3: Cumulative effects assessment is a sub-discipline of environmental impact assessment; it is “the**
209 **process of predicting the consequences of development, relative to an assessment of existing**
210 **environmental quality” (Dubé 2003), or “the process of systematically analyzing cumulative**
211 **environmental change” (Smit and Spaling 1995, Dubé 2003). As per Judd et al. (2015), it is a systematic**
212 **way to evaluate the significance of effects from multiple activities and to inform resource managers**
213 **about these effects. Local differences in methods exist, and are necessitated by location-specific laws,**
214 **policies, regulations, and planning systems (e.g., Gunn and Noble 2009)⁷.**

215
216 P16: How CEA is understood to work, how much policy significance is attributed to it, and how its
217 efficacy is to be measured is determined largely by its theoretical frame of reference (e.g., Bartlett and
218 Kurian 1999).

219
220 P17: As a sub-discipline of EIA, CEA shares EIA's “basic principles”, which Senecal et al (1999) suggest
221 require a process that is “purposive, rigorous, practical, relevant, cost-effective, efficient, focused,
222 adaptive, participative, interdisciplinary⁸, credible, integrated, transparent, and systematic”.

⁷ One may argue, on one hand, that inconsistent methods, allow for “flexibility and context-specific approaches” (Pope et al. 2013), which are presumably strengths of EIA and CEA practice; on the other hand, pluralism may be viewed as a weakness (Morrison-Saunders et al. 2014) that has resulted from poor theoretical grounding and lack of a unified conceptual model (Bartlett and Kurian 1999, Wärnäck and Hilding-Rydevik 2009, Retief 2010, Morgan 2012).

⁸ One defence of the call for interdisciplinarity was provided by Rubin and Kaivo-oja (1999), who cited “fundamental problems related to the idea of dividing contemporary human behaviour into social behaviour (sociology), economic behaviour (economics), personal behaviour (psychology), and political behaviour (policy sciences)”. These authors considered holistic analytical approaches more fruitful for “complex political, economic, social, technological and ecological systems”.

P18: CEA is, at least partially, a token bureaucratic requirement for development consent, which serves as a symbolic gesture to pacify environmentalists or reinforce conservation values (e.g., Bartlett and Kurian 1999, Karkkainen 2002).

P19: CEA's purposes and objectives require participants' values and ethics to be considered explicitly (e.g. Cashmore 2004).

P20: Being a sub-discipline of EIA, CEA can be viewed, at least partially, as an applied science, because it both generates knowledge and employs the scientific method. For example, hypothesis tests are used to evaluate the significance of effects. Knowledge resulting from such tests enhances our understanding of stressor-effect relationships, and ultimately reduces uncertainty in future appraisals (e.g., Cashmore 2004).

P21: Appraisal itself derives from the belief that the decision making process can be made more rational if options are carefully analyzed. CEA is chiefly a method of "generating, organizing, and communicating information" (e.g., Bartlett and Kurian 1999, Dubé 2003, Morgan 2012), which is then delivered to decision makers (Senécal et al. 1999, Hegmann and Yarranton 2011). Such information is intended to improve public decisions (Karkkainen 2002, Sheate 2010) about proposed actions (Rubin and Kaivo-oja 1999) by solidifying where the public interest lies, and by permitting one to estimate the probability that a given action will align with this interest (Wright 1986, Etzioni 1988, Hegmann and Yarranton 2011). "Decision makers are assumed to be acting in an objective and value-free manner, and their decisions are assumed to arise logically from a systematic and largely technical assessment of the evidence" (Benson 2003). Having access to information about the choices being considered, allows decision makers to overcome their personal biases, and more objectively consider issues germane to the decision

(Adelle and Weiland 2012). Knowledge is expected to translate directly into decision outcomes, and a separation of powers is deemed to exist between neutral, authoritative experts and the decision makers they advise (Owens et al. 2004, Pielke 2007). CEA is a logical, consistent, and systematic process that uses reason, science, and technical knowledge as a basis for, and justification of, decision making in a society that has an articulated singular (“unitary”) interest or goal (e.g., Lawrence 2000). As such, it is strongly rooted in positivism⁹ and rational decision theory¹⁰ (e.g., Benson 2003).

P22: As a basis for CEA, the technical-rational model of appraisal (which emphasizes the delivery of information to facilitate evidence-based decision making) is inadequate theoretically (because it fails to account for observed relationships between assessments and decisions¹¹; Pope et al. 2013, Russell-Smith et al. 2015), politically (because, in practice, decisions are influenced by ethical and political judgments; Bond 2003), and practically (because exposing its logical fallacies jeopardizes the legitimacy of both CEA appraisals and the courses of action brought about by particular decisions; Owens et al. 2004).

P23: Rationality is limited in human decision-making (Doyle 1999, Nooteboom 2000, Noble 2002, Cashmore 2004, Partidario and Arts 2005, De Martino 2006); the decision process is open to behavioural, political and institutional influence (Bartlett and Kurian 1999); and the complexity and information demands of CEA problems habitually exceed our capacity for strict rationality¹² (Doyle 1999, Sheate 2010). Elements of the decision-making process that tend to reduce rationality include

⁹ Positivism establishes logical verification, or mathematical proof, as a criterion for rational thought (Macionis and Gerber 2011).

¹⁰ Rational decision making is defined as “choosing among alternatives in a way that ... accords with the preferences and beliefs of an individual decision maker or those of a group making a joint decision” (Doyle 1999). Common criteria for rationality demand the decision-making process to employ logically sound and deductively complete reasoning (Doyle 1999).

¹¹ For example, experts cannot be neutral because of the adversarial way that the CEA plays out among proponents and opponents

¹² For these reasons, many authors substitute the term *bounded rationality* (e.g., Leknes 2001, Sheate 2010)

participants' ideological or political biases, poor governance of the process itself, corruption¹³, and misinformation. Furthermore, human decisions are influenced by context (i.e., the manner in which options are presented; Gunn and Noble 2009) because of how decision-making tasks are allocated to different loci in the brain — logical and rational thought being concentrated in the prefrontal cortex, and intuitive or emotional thought being concentrated in the amygdala (De Martino et al. 2006).

P24: "Post-positivist philosophies" (Adelle and Weiland 2012) stress the relativity of knowledge and the political context in which decisions are made. Improvements to the decision making process are made not primarily by better informing it, but by maximizing opportunities for debate and learning, by anticipating biases, and by managing the way power and influence are distributed among decision makers (Adelle and Weiland 2012).

P25: Although it is often viewed as a largely technocratic process, CEA still provides a forum for dialogue and learning (Owens et al. 2004, Owens and Cowell 2011), which can extend as spin-offs well beyond individual decisions to "influence the values and behaviours of organisations and society at large" (Pope et al. 2013).

P26: Deliberative rationality views the decision making process as an opportunity to debate difficult choices, demonstrate that opposing views have been taken seriously, and learn from the outcomes. A distinction can be made between the instrumental type of learning that characterizes the technical rational decision-making model and the deliberative conceptual learning that more generally enlightens decision makers by introducing new ideas and perspectives (Adelle and Weiland 2012).

¹³ Dominant interests tend to be insulated from the eventualities of bad decisions. In general, the greater the power, the lesser the rationality (Owens et al. 2004).

P27: CEA is, at least partially, a process that facilitates deliberation as a way of advancing environmental (also social and economic) justice. It represents a mechanism by which diverse competing interests and values are ratified by negotiation in a complex political and antagonistic arena that is often highly constrained by legislation, policy, and entrenched practices (e.g., Lawrence 2000).

P28: CEA is, at least partially, rooted in socio-ecological idealism (e.g., Lawrence 2000). By requiring bureaucratic organizations to employ environmentally-minded staff (who generate or review CEA appraisals), CEA constitutes a way to import environmental virtue into, and ultimately make the culture, institutional values, and routine operations of these organizations more environmentally centred (e.g. Bartlett and Kurian 1999, Lawrence 2000).

P29: CEA is, at least partially, a strategy for advancing ecological economics (e.g., Costanza 1992) because it integrates environmental goals into economics, and provides incentives for innovations that maximize environmental and economic returns (Bartlett and Kurian 1999); however in practice, this strategy is often thwarted because mitigation is emphasized to the point that alternatives are not properly explored.

P30: CEA is, at least partially, a way of enriching democracy because it establishes a transparent process by which consensus is sought via citizen involvement (e.g., Bartlett and Kurian 1999, Karkkainen 2002, O'Faircheallaigh 2010), communication, and collective visioning (Lawrence 2000).

C4: CEA has multiple objectives (e.g., Culhane 1990, Shultz 2012), which are loosely arranged around the themes of formalizing environmental values, establishing an ecologically viable socio-economy, and improving knowledge and governance (Pope et al. 2013). As a form of environmental appraisal,

CEA is not just a tool for informing and influencing decision-makers. It also changes the views and attitudes of its participants, and its influence can propagate outward through participants' social networks to influence entire institutions (Bond and Pope 2012).

P31: Ecosystems have a complex array of attributes that, taken together, are intractable: they are too complex to be fully considered within the scope of CEA (Damman et al. 1995).

P32: CEA evaluates effects on specific "valued ecosystem components" (VECs) or significant ecological features¹⁴ (e.g., Beanlands and Duinker 1983, Fisheries and Oceans Canada 2004, 2011, and 2014), which are considered to be¹⁵ important ecosystem attributes (Bérubé 2007, Gunn and Noble 2009, Canter and Ross 2010, Canter and Atkinson 2011, Dubé et al. 2013). VECs can be "physical things (e.g., a fish population), ecological processes (e.g., C sequestration), and even abstract concepts, such as ecological integrity or water quality (Damman et al. 1995, Dubé et al. 2013).

P33: VECs focus appraisal on a small number of important, valuable or significant ecosystem features, in order to provide a relevant and practically scoped reference point (Canter and Atkinson 2011).

P34: Consensus on which VECs to include in CEA may be achieved collaboratively according to social, cultural, economic, scientific or aesthetic concerns that arise from a professional scoping exercise, or

¹⁴ Given CEA's purpose as a sustainability instrument, one may argue that the term *valued ecosystem component* should be broadened as a measure of societal progress. In this scenario, indices could represent social, cultural, and economic dimensions of the "environment", thus allowing CEA to evaluate trade-offs among societal, not just ecological domains (Damman et al. 1995); however, some authors (e.g., Adelle and Weiland 2012) caution that more integrative CEA might backfire as environmental and social concerns are overwhelmed by more politically salient economic interests. For this reason, and to agree with the definition of *effect*, VEC is used here in its most restrictive sense.

¹⁵ Typically this consideration is societally broad, universal, or reflects consensus among CEA participants (Canter and Ross 2010)

from more inclusive procedures, such as public hearings, questionnaires, interviews, workshops, or media reports (Beanlands and Duinker 1983, Canter and Ross 2010).

P35: Indicators (or indices; e.g., Janetos and Kenney 2015) can be used as measurable surrogates for VEC condition or status (Gunn and Noble 2009), and they can be used to provide a numerical framework for CEA analyses (Canter and Atkinson 2011).

P36: VEC selection trades-off parsimony, which makes CEA tractable, with comprehensiveness, which makes it realistic (Duinker and Greig 2007).

C5: Valued ecosystem components (or their index-based surrogates) must be used to provide a tractable scope for CEA, and to ensure that attention is paid to “the most important environmental features and processes” (Damman et al. 1995, Canter and Ross 2010).

General guidance about indicators applies to CEA: indicators should be conceptually simple enough that their meaning can be conveyed to diverse audiences; they should be predictive; they should be sensitive and sufficiently accurate and precise to discriminate stressor-specific effects; and their sampling and data requirements should not be overly onerous and costly (e.g., Cairns et al. 1993, Niemi and MacDonald 2004, Bonada et al. 2006). Furthermore ...

P37: The value of a cumulative-effects indicator may be judged on the soundness of its surrogacy for one or more VECs (i.e., the degree to which it reflects the VEC’s condition).

P38: Given equal VEC surrogacy, the relative merits of candidate cumulative effects indicators may be assessed by how well they represent form and function of each ecosystem domain (i.e., habitat, biota, and interactions), by their sensitivity to changing conditions in each of those domains, and by their ability to diagnose causes of change.

P39: Stressor-based indicators evaluate an ecosystem's exposure to stress, but leave unanswered questions about the ecological relevance of that stress (Roux et al. 1999).

P40: Effect-based biological indicators measure ecosystem structure or function directly, because biota "integrate a cumulative response to environmental stress" (Dubé 2003, Munkittrick et al. 2000); but they leave unanswered questions about which stressor, or stressors, are being responded to (Roux et al. 1999, Gunn and Noble 2009).

P41: Stressor-based indicators measure habitat condition, and therefore integrate over only a single ecosystem domain; biological indicators integrate across all 3 ecosystem domains (habitat, biota, and their interrelationships), and they integrate across multiple stressors and their interactions.

C6: In principle, biological (effect-based) indicators are superior to stressor-based indicators for CEA. In practice, if ecological effects are detected, the stressors causing the effects must typically be identified (US EPA 2000, Dubé 2003); therefore both indicator types may be required to diagnose causes of, and model, ecosystem changes (Smit and Spaling 1995, Jones et al. 2002, Dube 2003, Dube et al. 2006).

P42: As a minimum, CEA must determine who specified VECs matter to, why they matter, how much they matter, how VECs will be effected by a specified set of activities, whether effects will be important given the past and present condition of the VEC, and what, if anything, could make up for any loss or damage to the VEC (Therivel and Ross 2007).

P43: In its most enlightened form, CEA constitutes a series of methods that assess the condition of the environment, describe causal pathways that link stressors and cumulative effects, predict risks and benefits associated with alternative management futures, and evaluate whether intended outcomes of the CEA decision were realized (Cormier and Suter 2008). This concept of CEA is rarely approached in practice.

P44: CEA’s operational practice includes the following 7 steps (adapted from Damman et al. 1995, Ross 1998, Canter and Ross 2010, Connelly et al. 2011, and Seitz et al. 2011)¹⁶:

1. Select VECs.
2. Define the physical and temporal boundaries of the appraisal.
3. Identify activities (past, present, future) that may affect VECs.
4. Characterize baseline (this step includes the selection of indicators, description of environmental condition, and determination of stakeholders that should be involved in the process).
5. Analyze and predict cumulative effects on VECs.
6. Determine significance of effects (given planned mitigation).
7. Monitor outcomes and CEA performance.

¹⁶ Flexibility to adapt to cultural, political, institutional, and legal contexts is imperative (Bond and Pope 2012), and results in regional variation in these steps.

P45: Decisions are made at each step in the CEA process, not just at the end (Benson 2003). CEA itself is a decision-making process.

P46. Although various decisions must be made as a CEA is undertaken, no objective, legitimate, and standardized criteria exist by which the soundness of these decisions can be evaluated. Illustrative examples include the lack of criteria for setting CEA's geographic and temporal scope (e.g., Shultz 2012), for establishing the breadth of issues to consider (e.g., which VECs, and which stressor-effect pathways to include [e.g., Duinker and Greig 2007]), for defining what constitutes an acceptable baseline against which present condition and future cumulative effects are gauged (e.g., Schultz 2012, McCold and Saulsbury (1996), for judging the significance of effects (Karkkainen 2002, Bérubé 2007, Scherer 2011), for determining who is responsible for carrying-out and paying for the appraisal, and for determining what function the appraisal is to have in the decision making process.

C7: Consensus on CEAs operational steps has been reached; however objective criteria for guiding decisions that must be made at each step are lacking, and a degree of pluralism is permitted so each CEA is tailored to its context (e.g., Bond et al. 2012). CEA practice habitually falls short of the aspirational ideal.

P47: CEA is complex methodologically, scientifically, and institutionally (Canter and Ross 2010). It deals with the future ("a complex mixture of consequences" [Rubin and Kaivo-oja 1999]) that unfolds because of present and past decisions but also because of innumerable other determinants that cannot be wholly accounted for (e.g., natural environmental processes, demographics, economics, scientific and technological advancements, the evolving zeitgeist, and random events; Gunn and Noble 2011).

P48: Complex systems (e.g., ecosystems) are inherently unpredictable, which means that uncertainty is unavoidable in CEA (Hegmann and Yarranton 2011, Chapman and Maher 2014). As per Karkkainen (2002), “our hopes of accurately predicting all the impacts associated with a development action are virtually nil” (Karkkainen 2002). The larger the area a CEA considers, and the longer its time horizon, the less certain conclusions about cumulative effects will be (Hegmann and Yarranton 2011).

P49: Given CEAs limited predictive abilities, activities under investigation are best viewed as experiments¹⁷ by which alternatives are explored (Duinker and Greig 2007, Canter et al. 2010, Schultz 2012).

P50: Monitoring indicates ecosystem form and function, allows the condition and variability of VECs to be quantified (Ball et al. 2013), signals when status is changing (e.g., Cairns et al. 1993, Jones et al. 2002), is used to test and refine predictive models (Davenport et al. 2008), and allows the performance of CEA and the decision-making process to be reviewed (e.g., Therivel and Ross 2007, Davenport et al. 2008, Schultz 2012), thereby making the CEA process more transparent and accountable (Karkkainen 2002).

P51: Monitoring facilitates adaptive management (Walters 1986) and “systemic learning” (Karkkainen 2002). It allows the CEA decision (about whether and how to proceed with one or more undertakings) to be retooled as a series of decision and adjustment points, arranged along a timeline into the future (Karkkainen 2002).

¹⁷ preferably low risk and reversible experiments

P52: Monitoring can reduce the costs of environmental appraisals because it allows proponents to trade-off some of the exhaustive front-loaded information costs for potentially lesser incremental costs that are spread over the life of the project (Karkkainen 2002).

C8: Monitoring and adaptive management are essential to CEA (Karkkainen 2002, Davenport et al. 2008, Seitz et al. 2011, Schultz 2012, Ball et al. 2013).

P53: It is more likely that decisions will be rational if the decision-making process is formal and transparent, and if there is an opportunity for external review and input, as afforded by public participation¹⁸. These attributes modify how decision makers approach their job, by tempering the influence of their own personal biases and values, and promoting thoroughness and disciplined rationality (Karkkainen 2002, Gibson 2012).

P54: Public involvement alleviates some of CEA's operational challenges by providing access to local knowledge, broadening the consideration of social values and environmental issues, and reducing the likelihood of litigation (Baxter et al. 2001, O'Faircheallaigh 2010). It also helps to build consensus around sustainability goals by fostering cooperation and confronting "NIMBYism"¹⁹ (Benson 2003).

P55: Public involvement adjusts the power relationships among participants in the decision-making process, making it more democratic, transparent, and accountable, and more responsive to societal values (Benson 2003, O'Faircheallaigh 2010, Sheate 2010). This, in turn, legitimizes the decision-making

¹⁸ *Public participation* is defined *sensu* O'Faircheallaigh (2010) as any interaction between government and corporate CEA parties and the public.

¹⁹ i.e., the Not-In-My-BackYard mindset

process, enhances public acceptance of its rulings, and stabilizes the participating institutions
(Karkkainen 2002).²⁰

P56: Public involvement lends CEA capacity to create more democratic and deliberative forms of
decision making (Bartlett and Kurian 1999), which ultimately advances human rights and social justice
(Benson 2003).

P57: Public involvement increases opportunities for reciprocal learning among CEA participants (Bond
and Pope 2012); It provides a mechanism by which the community comes to understand CEA’s goal and
limits, and the questions it can answer (Gallagher et al 2015); and it contributes organizational and
institutional capacity by which CEA can be improved iteratively (Sheate 2010).

P58: The earlier in the CEA process that public engagement occurs, and the more extensive that
engagement is, the more substantive its outcomes are (e.g., Canter and Ross 2010, Shirk et al. 2012,
Gallagher et al. 2015).

**C9: Public involvement in CEA is essential (e.g., O’Faircheallaigh 2010, Gallagher et al. 2015),
regardless of how one considers CEA’s value to partition among information-delivery (technical-
rational) and deliberative (post-positivist) outcomes (Morgan 2012).**

P59: Performance evaluation concerns effectiveness or efficacy; it provides a measure of how well an
action or method meets its own objectives (Sheate 2010).

²⁰ According to Birkeland (1999) public participation can be dangerous when emphasized to the extreme, because
it can “mask the need for deeper institutional reforms”.

P60: Enabling legislation and operational guidance evolve, at least partly, based on assessments of efficacy (e.g., Bond and Pope 2012).

P61: Government priorities of stimulating economic growth and creating employment cause CEA to be subjected to intense scrutiny. Particularly during times of economic (thus political) upheaval, governments are prone to water-down environmental appraisal, and this is facilitated where performance hasn't been assessed or results have been seen as unfavourable (e.g., Gibson et al. 2012, Morgan 2012, Middle et al. 2013 and Morrison-Saunders et al. 2014).

P62: It is notoriously difficult to design a defensible study by which CEA's effectiveness can be judged, and our ability to generalize beyond a given CEA's political, cultural, legal, and institutional context is limited (Morgan 2012). It is tricky to specify what influence CEA ought to have on a given decision-making process (Cashmore 2004), and separating out the consequences of CEA from the many other factors that influence decision-making is problematic (Sheate 2010). Furthermore, it is impossible to judge what would have happened in the absence of a given CEA appraisal, because controls are generally not available and decisions are not replicated. It is also impossible to determine whether any given decision (e.g., the granting of development consent) is correct because no objective criterion for correctness exists (Cashmore 2004), and because the totality of effects will not be realized until some future time.

P63: Performance evaluation is constrained by the lack of clarity with which CEA's nature and purpose is understood (e.g., Morgan 2012). CEA's pluralistic theoretical underpinnings mean that its performance may be assessed relative to ecological, social, political, economic, and learning outcomes (Lawrence 2000, Bond and Pope 2012). As Adelle and Weiland (2012) illustrated, a researcher with a positivist bent

(presumably interested in the soundness of assessment methods and the quality of predictions) may cite misuse of, or inadequate, monitoring or modeling tools as a CEA weakness. A researcher from the post-positivist tradition (perhaps interested in learning and how evidence is used in the decision making process) might cast aside analytical methods as irrelevant but single out inadequate deliberation on available options as a crucial inadequacy. Similarly, a researcher assessing CEA's operational steps may view any gap between goals and results as a critical weakness; whereas a researcher interested in the politics of appraisal may consider such gaps simply as evidence that CEA's underlying motivation is mainly symbolic.

P64: Pluralistic frameworks for evaluating performance have been proposed by several authors (e.g., Bond et al. 2012, Middle et al. 2013); however, translating these narrative frameworks into evaluative criteria is usually problematic because of conceptual difficulties associated with ill-defined terms, and because indicators are either not apparent, not routinely monitored, or difficult to quantify. For example, Bond et al. (2012) suggested evaluating the appraisal process based on its "procedural effectiveness" (i.e., by considering the degree to which implementation agrees with professional and institutional standards of practice)²¹, "substantive" and "normative" effectiveness (i.e., by measuring to what extent the outcome of the appraisal aligns with the reasons for doing the appraisal)²², "transactive effectiveness" (i.e., by assessing the degree to which time and money investments in the appraisal are justified by its outcomes)²³, engagement (i.e., by determining to what extent stakeholders are accommodated into, and satisfied by, the appraisal process)²⁴, and learning (i.e., by quantifying the degree to which the appraisal facilitates "instrumental and conceptual" learning²⁵). Middle et al. (2013)

²¹ But how is agreement defined?

²² But authors have not reached consensus about the importance of CEA's various motivations.

²³ But how can this justification be critiqued objectively?

²⁴ But what is the optimal amount of engagement?

²⁵ i.e., instrumental and conceptual learning are not discrete, and both are difficult to quantify

suggested evaluating CEA performance based on the comprehensiveness of the CEA requirement (i.e., the proportion of proposed activities subject to CEA appraisal)²⁶, scope (i.e., how adequately VECs represent important ecological attributes)²⁷, “objectivity, openness, and transparency” (of both the CEA process and the decision-making process it is a part of)²⁸, quantity and quality of public participation, timeliness (i.e., how early in the decision-making process CEA occurs, earlier being better because decision makers have flexibility to more fully consider alternatives the earlier in the process the appraisal is situated [Gunn and Noble 2009]), the degree to which CEA outcomes guide the evolution of environmental policy, capacity for adaptation (i.e., how flexible the CEA process is, and how much learning and innovation results from it)²⁹, efficiency (i.e., money and time costs)³⁰, rationality (i.e., how predictable the decision outcome is, given the nature of information that surfaces during the CEA appraisal)³¹, and follow-up (i.e., the degree to which the CEA outcome is legally binding, and how closely resultant cumulative effects match those predicted).

P65: CEA’s ultimate goal is *sustainability or environmental protection*; holistic, quantitative, and objective surrogates for these embattled terms are the Holy Grail of CEA performance evaluation.

P66: Evaluative techniques from disciplines such as results-based management and risk assessment can be adapted for CEA. For example, logic models (borrowed from results-based management) allow one to create a simplified description of a program, initiative, or intervention that illustrates the logical relationships that connect invested resources with activities and outcomes (Taylor-Powell et al. 2003); Bow-tie analysis, a risk-assessment technique (IEC/ISO 2009), can be adapted for CEA by elucidating

²⁶ But how can the optimal degree of comprehensiveness be established objectively?

²⁷ Importance is subjective.

²⁸ But what degree of openness and transparency is necessary? Can there be too much?

²⁹ But attributing changes to any particular CEA will be problematic.

³⁰ But how much *should* CEA cost?

³¹ But how will predictability be assessed? Is predictability really a measure of efficacy?

what measures are in place to prevent cumulative effects associated with a given activity or policy, and by evaluating how effective those measures are, and how fully they are implemented (e.g., ICES 2014).

C10: Multifaceted evaluation of CEA's efficacy and efficiency is required if CEA is to be endorsed and enlightened in the future, but methods for evaluating CEA are embryonic.

P67: Alternative patterns of human activity can be examined in CEA, given a process that allows cumulative effects associated with these patterns to be assigned different probabilities (Rubin and Kaivo-oja 1999).

P68: Cumulative effects assessment requires the effects of multiple stressors to be understood, both singly and in combination (Ball et al. 2013, Judd et al. 2015).

P69: Processes within ecosystems can magnify minor localized effects, requiring a variety of interactions to be considered, for example stressor interactions with time, with space, and with other stressors.

P70: Quantitative CEA requires large complex datasets (describing multiple actions, VECs and their surrogate indicators, and predictors that quantify stressor exposure), and these datasets must be analyzed from various spatial and temporal perspectives (Atkinson and Canter 2011).

P71: A variety of stressor-based and effect-based indicators have been described, such as habitat attributes (e.g., May et al. 1997 [watershed land cover], Jennings et al. 1999 [lake shoreline substrates], Shifley et al. 2008 [forest attributes]), chemical attributes (e.g., Smith and Owens 2014), metabolomic markers (e.g., Viant 2009, Van Aggelen et al. 2010) and indices of the taxonomic or functional structure

of communities (e.g., Norris and Georges 1993, Dolédec et al. 2006, Borja et al. 2011,). These indicators are available for adoption by CEA practitioners wishing to associate stressors with effects on VECs (Canter and Atkinson 2011)³².

P72: Remote sensing and computerized systems for geospatial analysis provide CEA practitioners the ability to create, store, manipulate, analyze and visually display large amounts of geographically referenced data (Atkinson and Canter 2011); these technologies can be used to quantify stressors, and to relate stressors and effects, in a “spatially explicit manner” (Davenport et al. 2008, Atkinson and Canter 2011, Ball et al. 2013, Seitz et a. 2013).

P73: Scientific methods for investigating stressor effects are well developed, and they range from experimentation to a variety of mechanistic and statistical modeling approaches.

P74: Modeling is used in CEA to associate indicators of ecosystem form or function with natural factors or stressors (Seitz et al. 2012, Ball et al. 2013), to explore futures associated with different scenarios of human activities (e.g. Duinker and Greig 2007; Russell-Smith et al. 2015), and to guide the design of monitoring schemes (Davenport et al. 2008). Modeling can be as simple as hypothesis-of-effect diagrams or interactive matrices (e.g., Smit and Spaling 1995), which illustrate suspected causal pathways that link stressors and effects, or they can be as complicated as “meta-model” frameworks (e.g., Smit and Spaling 1995), which combine simulation models to investigate stressor-effect relationships at a variety of spatial and temporal scales, or across a variety of ecological and societal dimensions. Statistical models for quantifying cumulative effects include regression (which associates a single response with one or more predictors; e.g., Steel and Torrie 1980, Sorensen et al. 2008),

³² Indicators of natural capital and ecosystem services (which may be called for, given alternative concepts of VECs) are also available (e.g., Hayha and Franzese 2014).

606 redundancy analysis (which associates multiple response measures with multiple predictors; e.g.,
607 Legendre and Legendre 2012), and variance components analysis (which partitions the variation in one
608 or more response variables that is associated with selected predictors and their interactions; e.g., Peres-
609 Neto et al. 2006). Interactive (e.g., additive or multiplicative) terms can be included in such models to
610 account for combined stressor effects.

611
612 P75: Modeling involves trade-offs between scale and precision, and between conceptual complexity and
613 computational complexity (Shifley et al. 2008).

614
615 P76: Retrospective analyses that link VEC trends with past activities provide a foundation for prospective
616 *futuring* (i.e., use of methods that predict future conditions; Therivel and Ross 2007, Canter and
617 Atkinson 2011).

618
619 P77: Futuring attempts to describe a plausible range of outcomes, given the uncertainty of future
620 actions (Duinker and Greig 2007, Therivel and Ross 2007, Canter and Ross 2010). Its point is to “explore
621 risks and sensitivities”, which can “profitably be done without pinpointing the exact development future
622 that will unfold into reality” (Duinker and Greig 2007). Futuring methods include scanning, trend
623 analysis, extrapolation, and projection (which characterize historic trajectories and project these trends
624 into the future, based on the assumption that causal mechanisms will persist)³³, scenario building (which
625 is the process of creating alternative depictions of the future that may play out as a consequence of
626 different decisions being made), polling or brainstorming (which includes the popular Delphi method
627 [e.g., Lang 1998], in which questionnaires are used to structure expert discussions and arrive at

³³ To address complexity and uncertainty, it is wise to combine backcasting (which specifies desirable future scenarios, and explores various means of attaining them) with forecasting (which specifies undesirable future scenarios, and explores various means of avoiding them).

consensus about future ranges of key variables), simulation modeling (which creates mathematical extrapolations based on mechanistic relationships between stressors and effects), gaming, historical analysis, and visioning (Cornish 2004, Duinker and Greig 2007).

P78: Methods of human and ecological risk assessment, which examine risks associated with “aggregate exposures to multiple agents or stressors” (e.g., US EPA Risk Assessment Forum Cumulative Risk Technical Panel 2003, Gallagher et al. 2015) can be adapted for CEA.

P79: Weight-of-evidence methods (e.g., Burton et al. 2002, Chapman and Maher 2014) for integrating multiple (possibly conflicting) lines of evidence that associate multiple stressors and their cumulative effects are available, and they range from qualitative use of causal criteria and logic models to integrated quantitative statistical analyses (Linkov et al. 2009).

P80: CEA should be “rigorous” (i.e., it should use defensible scientific methods that are appropriate to the questions posed; Senécal et al. 1999); however, practical limitations to scientific methods become apparent in CEA (Seitz et al. 2011). For example, appropriately replicated factorial experiments designed to test multiple-stressor effects (and their interactions) on biological endpoints require very large experimental apparatuses and associated infrastructure, and become difficult to implement because of personnel, equipment, and space constraints (Fisher 1960, Thorngate 1976, Steel and Torrie 1980). Similarly, complex statistical models, including interactive terms (which describe shared variance among predictors) and cumulative terms (which represent additive or multiplicative combinations of predictors) require large datasets that may resist compilation.

P81: Our knowledge about stressors and their effects on most ecosystems remains insufficient as a starting point for CEA (Seitz et al. 2011, Venier et al. 2014).

P82: A rough description of cumulative effects is generally all that is needed to identify appropriate management options (Therivel and Ross 2007).

C11: Basic knowledge about stressors and effects is rudimentary. Nonetheless, “the ecological literature is rife with ... reports outlining various predictive models for forecasting effects of particular developments on specific ... VECs” (Duinker and Greig 2007). Numerical methods for quantifying, assessing, modeling, and predicting cumulative effects are available. On one hand, our capacity for prediction is often small, and there are practical limits to the number of factors that can be tested experimentally or modelled; on the other hand, crude approximation of cumulative effects is sufficient in most CEA contexts (Therivel and Ross 2007).

P83: The subject of CEA may be an existing, proposed or hypothetical project or undertaking (i.e., project-based CEA; e.g., Gunn and Noble 2009, Seitz et al. 2011) or may be an idea, policy, regulation, law or similar strategic instrument (i.e., strategic CEA; Harriman and Noble 2008, Noble 2008, Gunn and Noble 2009, Connelly 2011, Gunn and Noble 2011, Hegmann and Yarranton 2011).

P84: CEA may be undertaken with a restricted spatial and temporal frame of reference, as is common with project-based CEA, or it can be undertaken at a scale that is not bounded by the parameters of a specific undertaking (e.g., at the regional³⁴ or watershed scale [Spaling et al. 2000, Ball et al. 2013, Dubé

³⁴ *Regional scale* is a rather ill-defined term that describes an area that is much larger than the footprint of a specific project, especially one that is ecologically or jurisdictionally relevant (e.g., a watershed, ecoregion, or municipality)

et al. 2013, Smith and Owens 2014]³⁵, and with a longer-term perspective, as is common with strategic CEA [Gunn and Noble 2009]]³⁶.

P85: Current practice in project-based CEA reflects a mindset of ecological abundance, with environmental assessment at the scale of individual projects, and from the perspective of regulatory compliance; its scientific integrity is generally limited to the extent necessary for project approval (Seitz et al. 2011); and it promises mitigation of effects, though performance is assessed predominantly with measures of efficiency, not efficacy (Gunn and Noble 2009, Noble 2010). As a result, project-based CEA is unable to cure incremental effects like biodiversity loss (Connelly 2011) and other products of the present dogma in which continual development is pursued in a finite biosphere (Schnaiberg and Gould 2000). Furthermore, "...CEA operates in three silos. Project proponents operate in the silo of stressor-based approaches to identify and mitigate project stressors, with governments as gatekeepers. The scientific/academic community operate in the silo of effects-based science to understand ecosystem functioning and environmental effects in response to landscape disturbances. Land-use planners and managers are focused on broader environmental planning and social matters, while incremental impacts at the project level continue to accumulate" (Noble 2010).

P86: "Cumulative effects assessment ultimately is an attempt to describe environmental change driven by forces far larger than any one project" (Hegmann and Yarranton 2011), and to compare the

³⁵ Given CEA's eco-centricity, several authors (e.g., Gunn and Noble 2009) assert that regional units should be defined ecologically (e.g., as watersheds), not politically or administratively (e.g., as municipalities).

³⁶ Some authors classify sub-disciplines of EIA (e.g., strategic environmental assessment, regional strategic environmental assessment, cumulative effects assessment) according to how "vertically integrated" or "tiered" they are (e.g., Pope et al. 2013). A project-based appraisal of development effects for the purpose of regulatory approval would be considered lower-tier, with restricted geographic scope, and little vertical integration; whereas, an appraisal of the cumulative effects of a regional development policy, would be considered upper tier, because of its broad geographic scope and its integration with decision-making processes in planning and policy realms. The term *strategic* has also been used to describe the degree to which alternative options are considered in CEA, and how early in the decision process this consideration occurs (more comprehensive considerations of options, occurring earlier in the process, being considered more strategic; e.g., Gunn and Noble 2009).

sustainability of development alternatives, relative to the present day status quo. There are many advantages of a regional approach to CEA: efficiencies associated with collective information gathering and sharing (including vital information about baseline conditions and historical trends); the ability to set regional thresholds for acceptable environmental condition; the opportunity to evaluate the collective effects of multiple projects or strategic instruments in a streamlined regulatory process; and empowerment of, and greater cooperation between, participating organizations who advance diverse visions of a locality's development (Spaling et al. 2000, Gunn and Noble 2009, Connelly 2011).

P87: Challenges associated with scaling-up CEA from the project scale to the regional scale partly arise from increased complexity of stressor-effect relationships, and partly from greater institutional complexity (Sheelanere et al. 2013). The most basic problem concerns "how to aggregate cumulative effects beyond the scale of the individual project" (Gunn and Noble 2011). Indeed, the transition to regional CEA thinking requires us to change our current perception of environmental issues as being specific to the location of a given undertaking. It also requires the dynamics of our social-ecological systems to be understood well enough that limits, targets, and indicators of change can be specified (Gunn and Noble 2011). One may also argue that a purely biophysical definition of *effect* may not be sensible for regional CEA, for which interactions among socio-economic and ecological attributes are central considerations.

P88: The project-based approach to CEA is "narrow, reactive, and divorced from broader planning and decision-making contexts"; it fails to adequately predict and control continuous development and its effect on the environment" (Gunn and Noble 2011, Seitz et al. 2011).

P89: CEA has not advanced adequately to encompass regional and strategic perspectives. Beyond the individual project, CEA has focused on describing baseline environmental conditions, rather than on reporting trends, analyzing scenarios, and evaluating alternative futures, so it has provided limited advice to planners and decision makers (Harriman and Noble 2008, Gunn and Noble 2009).

P90: Reciprocal learning can occur between project-based and more strategic and regional forms of CEA (Connelly 2011, Seitz et al 2011). "A regional approach can set the context needed for scoping, assessing and managing cumulative effects attributable to individual projects, whereas project-specific CEAs should build on the regional understanding and suggest in some detail how to manage the cumulative effects...(of a)...specific project" (Baxter et al. 2001).

C12: CEA is best undertaken in a strategic and regional context (Baxter et al. 2001); however the current practice falls short of ideology (Gunn and Noble 2011).

P91: Planning is concerned with articulating societal priorities and managing change via the allocation of resources (Hegmann and Yarranton 2011); it establishes the context within which sustainability is to be implemented" (Gunn and Noble 2011).

P92: Responsibilities for EIA and CEA are more commonly the jurisdiction of "agencies having a development mandate, rather than an environmental mandate" (Pope et al. 2013). Regional planning authorities are the "logical CEA proponents" (Gunn and Noble 2009) because of the "unprecedented need for the integration of sustainability principles in the development of regional policies, plans, and programs" (Gunn and Noble 2009).

P93: Instructive feedback loops exist between CEA and planning. Sustainability goals provide a benchmark against which the significance of cumulative effects may be judged (Hegmann and Yarranton 2011); whereas, CEA organizes, analyzes, and presents information in a way that allows the sustainability of various alternatives to be assessed (Hegmann and Yarranton 2011). Indeed, reciprocal feedback loops extend even more broadly across societal domains and academic disciplines, because more, and better, CEA means that the outcomes of human activities can be better predicted. The more formal, quantitative, and strategic the planning and regulatory process, the better CEA can be tuned, and the more meaningfully its performance can be evaluated (Duinker and Greig 2007, Chapman and Maher 2014).

P94: Interdisciplinary communication and reciprocal learning permit efficiency gains to accrue as CEA is iterated. For example, scenario development becomes more efficient and cost effective if premises, assumptions and scenario types (e.g., “business as usual”, “pessimistic”, “disastrous”, “optimistic”, or “miracle”; Cornish 2004, Duinker and Greig 2007) are shared.

C13: CEA and planning are inseparably linked, and communication between these disciplines allows for reciprocal learning.

P95: The 96 premises and 13 conclusions listed above characterize what CEA is, how and why it is done, and how and why it *ought to be* done; however these statements are incomplete and occasionally contradictory.

C14: As is true of EIA (Cashmore 2004), CEA's theoretical basis is inadequately unified and detailed as "... a series of somewhat nebulous models operating along a broad spectrum of philosophical beliefs and values"; Table 2).

<<INSERT TABLE 2 HERE>>

CEA's Big Problems

Cumulative effects assessment should be innate. Our lives proceed via a great number of decisions, the consequences of which are —or, at our own peril, are not— considered pro-actively. When the oven timer rings, signaling that the casserole is cooked, a plausible future scenario includes burnt hands and a trip to the emergency room. Burning the hands leads to pain and misery, infection, loss of function, and ultimately threatens survival (especially if done more than once). Prudent mitigation by the cook is achieved by donning oven mitts before dinner is removed from the oven. Difficulty with CEA arises when we scale-up from the individual level to the collective, societal, and institutional levels. This scaling-up is most easily done given an ethos of ethical objectivism, in which the collective good is paramount, principles of conservation or preservation are highly valued, and individuals are held accountable to these morals. By contrast, many authors have argued that we are in an age of individualism, consumerism, cultural and ethical relativism, and personal non-accountability (e.g., Rubin and Kaivo-oja 1999, Truss 2005, Hamilton 2010). These social viewpoints ultimately influence CEA decisions because they influence how development-related trade-offs³⁷ are perceived (Coates and Leahy 2006, Nunneri et al. 2008). Fully harnessing the potential of EIA and CEA as sustainability instruments requires innovations that overcome, redirect, or reprogram these social norms.

³⁷ Trade-offs arise commonly in CEA where a favourable response in one indicator can only be achieved via the adverse response of another.

784
785 Cumulative effects laws, regulations, and policies on their own are universally incomplete and
786 underachieve (Duinker and Greig 2006). Furthermore, it is important to appreciate that in most
787 democracies the supreme constitutional principle is individual liberty. When implementing a regulation
788 or law, the onus is on ensuring protection of individual rights and freedoms (not the environment). For
789 this reason, legislators often take an indirect approach to environmental issues by prohibiting certain
790 impacts, rather than limiting human activities (Pers. Comm. Cormier 2015). All the while, the blame-
791 game circumvents meaningful confrontation of cumulative effects: plan-makers argue that effects are
792 caused by individual actions, and individuals argue that their actions are constrained by government
793 policies (Therivel and Ross 2007).

794
795 In addition, legal, regulatory, and institutional frameworks are largely insufficient to enable CEA's
796 diverse outcomes to be realized (Ball et al. 2013), uncertainties about jurisdictional roles and
797 responsibilities are pervasive (especially when CEA is undertaken at a regional cross-jurisdictional scale;
798 Damman et al. 1995), and connections to science and planning are rudimentary. For example, the
799 Chinese case study written by Wang et al. (2003) described a series of systemic institutional problems,
800 including: project-based institutional attention being focused on air, water, and soil pollution, with social
801 and ecological cumulative effects being largely ignored; complex and confusing lines of responsibility
802 and accountability that vary by jurisdiction, resulting in regional variation in the quality of appraisals;
803 waning institutional capacity, caused by insufficient funding as departmental responsibilities and
804 workloads have expanded; perverse inter-agency incentives that arose from environmental regulators
805 being funded by pollution levies; and weak enforcement.
806

CEA does cultivate some obviously good practices. For example, it upholds informed, transparent, and accountable decision-making, and it results in irreconcilable disputes being referred to the judicial system (Hegmann and Yarranton 2011); however, appraisal, and its role in the decision-making process, is inadequately conceptualized (Owens et al. 2004), and its ostensive purposes are difficult to translate into definable outcomes, so it's not clear how to use CEA to make demonstrably better decisions (Cashmore 2004). CEA's integration with the decision-making process stresses information delivery to decision makers, as a way of promoting rationality. But this is an unstable philosophical basis for CEA because it neither accounts accurately for the scientific assessment-decision nexus (i.e., CEA rarely informs decisions in a straightforward linear fashion, and decision makers fail to use vast quantities of information produced for their use [Russell-Smith et al. 2015]), nor for the decision making systems that exist in modern democracies (in which there is no singular societal vision; Owens et al. 2004). As a result, CEA is both naive and potentially dangerous — it allows “ethical and political choices (to) masquerade as technical judgments” (Owens et al. 2004), and the resulting tokenism tends to reinforce a society's norms and distribution of power (which are often at odds with CEA's promise of sustainability).

In recent years, CEA has been seen in a new light, its focus “less on an individual decision and more on long-term outcomes through processes of transformation” (Pope et al. 2013); then again, CEA (and EIA) have failed to realize their pledged deliberative outcomes. One of the main reasons for this deficiency is superficial public engagement, whereby members of the public are invited only to review materials and provide comment (usually too late in the CEA process to have much impact) . For example, Sinclair et al. (2012) published (in the EIA literature) a particularly scathing account of citizens' experience in the Emera Brunswick natural gas pipeline hearings in New Brunswick, Canada, which showed that “most elements of meaningful participation were not satisfied”: information sessions intended to brief public

participants were overly complicated, confusing, and formal, and failed to prepare participants for the intimidating adversarial and quasi-judicial review process; funds provided to public participants were meager, arrived too late in the process, and carried too many conditions to level the playing field among parties to the appraisal; the review panel failed to adjust the scope of the assessment, despite repeated appeals from the public; time horizons for phases of the appraisal, and hearing schedules, did not accommodate the schedules of public participants (most of whom had full-time jobs and no staff to assist with preparation for hearings); open discussion about how issues raised during the process could be solved were discouraged by a review process that was based on cross-examination; and professionals in the process undervalued local public knowledge (all of which left participants feeling “bitter, disrespected, marginalized, and wasted”. As several authors have reported (Adelle and Weiland 2012, Pope et al. 2013) more empowering and transformative models of engagement have been slow to catch on.

Aside from CEA’s theoretical basis, “resource-based targets or limits are keys to stimulating careful thought about, and robust management of, cumulative effects” (Therivel and Ross 2007) because they allow *significance* and *acceptability* to be specified quantitatively. Yet societies pay only lip service to the goal of sustainability, and *sustainability* is not defined in a suitably operational sense to provide a sound basis for CEA (Spaling et al. 2000, Connelly 2011, Hegmann and Yarranton 2011, Dubé et al 2013). As a result, solutions to cumulative problems are often deemed unpalatable, their ownership is dismissed as someone else's remit (Therivel and Ross 2007), and economic interests easily outweigh environmental interests (e.g., Adelle and Weiland 2012). A variety of methods exist for setting indicator targets relative to reference levels or other baselines, non-linear stressor-response relationships, and social norms³⁸ (e.g., Samhoury et al. 2011); but there are also a variety of challenges, as Samhoury et al. (2011)

³⁸ Social norms define what is generally expected within a given cultural setting, and can be quantified statistically from survey data (Samhoury et al. 2011).

described with reference to marine-ecosystem targets for Puget Sound. For example, it is difficult to calibrate present ecosystem form or function to a historic or spatial reference condition in which human impacts were absent. Furthermore ecosystems vary dynamically over time and space, meaning that historical and spatial baselines are arbitrary.

Barriers to interdisciplinary research are another problem. As Rubin and Kaivo-oja (1999) wrote, “the boundaries between natural sciences, social sciences, and the humanities...have blurred”, and this blurring needs to take place given that complex sustainability problems have to be solved by changing the interactions between social and ecological systems (Klein 2004, Binder et al. (2013); however, methods of interdisciplinary research and collaboration are rudimentary (e.g., Sheate 2010, Morrison-Saunders et al. 2014), and disincentives abound — e.g., obstructive prejudgments that social and natural scientists make about one another, the lack of opportunities for financing interdisciplinary work, differing discipline-specific publishing expectations, power differentials that exist in diverse research collaborations, and the need for time consuming procedures to manage team dynamics, and clearly articulate research goals and methods (Campbell 2005, Neilson-Pincus et al. 2007).

Many how-to documents have been written for CEA practitioners (e.g., Hegmann et al. 1999, Cooper 2004, Munier 2004, Glasson et al. 2013), but guidance on how to operationalize CEA remains incomplete and difficult to generalize, and a variety of methodological challenges remain. This is true because decisions have to be made at each step of the CEA process, but objective and universal criteria for guiding those decisions do not exist. Societal values and sustainability goals vary from place to place, which means that the scope of issues to include in CEA assessments is impossible to standardize, as are decisions about which VECs and indicators to use (e.g., Baxter et al. 2001, Thirevel and Ross 2007, Ball et al. 2013). The outcome of this subjectivity is that VECs are often included only if significantly impacted

878 by the undertaking(s) being appraised, so environmental components that are incrementally affected in
879 a minor way are excluded, and deaths by a thousand cuts can continue unabated (Bérubé 2007).
880 Furthermore, the appropriate spatial and temporal scale for a given CEA depends on the subject of the
881 CEA appraisal, and on selected VECs and indicators, among other factors; however, chosen surrogate
882 indicators may not be predictable enough to be used in CEA scenario models, and ecological indicators
883 that can be modeled with suitable precision may not be relevant to local VECs. Objective thresholds for
884 the significance of effects are elusive given ambiguity of the term *threshold*, and the fuzziness of
885 sustainability goals (McCold and Saulsbury 1996, Bérubé 2007, Ball et al. 2013). Methods of evaluating
886 performance are difficult to standardize because CEA's pluralistic information-delivery and social
887 outcomes are treated as more or less legitimate by different authors.

888
889 According to Schultz (2012), "Determining the appropriate geographic and temporal scales of analysis is
890 one of the most perplexing aspects of CEA". This is partially because stressors and effects commonly
891 occur at different spatial and temporal scales (Seitz et al. 2011). But also because the larger the area
892 covered by a CEA, the less important local issues (e.g., a new factory or shopping mall) will be, the more
893 important landscape-scale phenomena (e.g., pervasive impacts associated with the manufacturing or
894 commercial sector) will be, the less likely it will be that a particular effect will be singled out as
895 significant, the less likely it will be that CEA boundaries will align with administrative ones, and the less
896 clear it will be where the responsibility for follow-up action lies. Similarly, the longer the time-frame
897 considered, the less certain CEA analyses will be (Therivel and Ross 2007, Seitz et al. 2011).

898
899 Mathematical procedures for associating stressors and effects are relatively well described, but the
900 required monitoring data is generally lacking (Damman et al. 1995, Scherer 2011, Schultz 2012, Ball et al.
901 2013, Venier et al 2014), and is "expensive and time consuming to gather" (Connelly 2011). Obviously,

more complex models call for more complex input datasets and underlying monitoring programs, so a vicious cycle is apparent (Gallagher et al 2015). The information that is available is “highly uncertain and variable in quality” (Karkkainen 2002), and is, for the most part, not efficiently shared among CEA participants (Damman et al. 1995).

Hutchinson’s (1959) concept of the niche provides a strong theoretical basis for thresholds, because it posits that organisms can tolerate only a finite range of conditions relative to any environmental dimension; however, in practice, multiple definitions of the term *threshold* exist. For example, the term can be used to describe a fundamental shift in community structure or dynamics, or a non-linear response of a population to one or more disturbances. Furthermore, there are many levels of biological organization at which thresholds may be evident; there is a limitless number of potential response variables for which thresholds could be derived; and different statistical approaches will result in different thresholds. Exploring only a small number of these is costly and requires an immense amount of data, but only a small sub-set of identified thresholds will be relevant to VEC conservation (Johnson 2013). Statistical significance may be easy to demonstrate, for example, as the value of a given indicator being outside of a statistically defined “normal” (e.g., Kilgour et al. 1998) but ecological significance is another matter. Furthermore, the societal significance and relevance of a cumulative effect is open to debate, given how vague the concept of sustainability is (Scherer 2011, Moldan et al. 2012).

In addition to the subjectivity of decisions made in the CEA process, complexity and uncertainty are fundamental difficulties, commonly invoked to describe, for example: the diversity of biological and physical land-use effects, stressor interactions, spatial and temporal lags between stressors and effects, non-linear relationships, and positive and negative feedback loops (Spaling and Smit 1993, Thirevel and Ross 2007, Seitz et al. 2011, Ball et al. 2013). In Hegmann and Yarranton’s (2011) pessimistic assessment,

926 “even if practitioners employ the most advanced and complex analysis and the best that analytical
927 thought may offer (CEA) still delivers just words and numbers buried within limitations, assumptions and
928 uncertainties” (Hegmann and Yarranton 2011).

929

930 It is clear that CEA’s big problems are not discrete. Rather, they overlap and feed off each other. They
931 are also replicated throughout the other sub-disciplines of EIA, where they have caused confusion and
932 exaggerated methodological incompatibilities (Canter et al. 2010, Morrison-Saunders et al. 2014).

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Recommendations

CEA should be considered one part of a precautionary sustainability strategy, not as a stand-alone

solution for dealing with development-related environmental effects: Earth can neither support our

current resource demands nor assimilate the ecological stresses associated with further demands

(Wackernagel and Rees 1998). Ecological trends suggest deepening unsustainability (Vitousek et al.

1997, Foley 2005, Steffen et al. 2007). We are caught in a vicious cycle of ecological exploitation that

leads to ecosystem damage, the exhaustion of resources, and a spiral of continuing degradation, as

livelihoods are undermined (Schnaiberg and Gould 2000, Gibson 2012). Environmental conservation and

development may both be seen as societal imperatives, but ecological considerations ultimately must be

the trump card. Proposed human endeavors should move forward only if they are expected to pay long-

term ecological dividends. A mitigative approach, which slows down incremental losses, is inadequate

because it falls short of the principle of no net loss (e.g., Benson 2003), and the needed reversals of

present ecological trajectories (Bond et al. 2012). As a starting point, the sustainability goals of the

United Nations General Assembly (UNGA 2015), which are largely directed at the World's governments,

may help to change societal values so they become more aligned with CEA. Furthermore, the influence

of the UN targets could be maximized by also mobilizing extra-governmental advocates for change,

which Hajer et al. (2015) suggested could be done by invoking complementary notions, such as,

"planetary boundaries" (which stress the urgency of environmental concerns and the need to take

responsibility for ecosystem goods and services), "the safe and just operating space" (which highlights

interconnectedness of social and environmental concerns), and "the energetic society" (which

stimulates "green competition" and technological innovation). All of these concepts should be

operationalized with relevant indicators and monitoring (e.g., Hák et al. 2016), some of which will be of

use in CEA.

958 **Recognize that people and political systems are not programmed to think in terms of long-term**
959 **strategy (e.g., Diamond 2005), and don't allow CEA (or EIA) to usurp precaution³⁹:** Considerable
960 societal inertia exists that is counter to the principles of sustainability, and EIA's 40-year track record is
961 not stellar. There is, however, hope for CEA, which can be viewed as a way to enforce strategic thinking.
962 As regards development, logically sound precaution should be operationalized in the decision making
963 process as: *avoid, minimize, restore, offset*. CEA traditionally encompasses the first two of these
964 strategies. Compensatory restoration and offsets (e.g., Therivel and Ross 2007, Connelly 2011) are much
965 needed complements, which are consistent with the idea of no net loss, and can "make room" for future
966 developments (Canter and Ross 2010) where further consumptive expansion is justifiable because of
967 current deficiency. CEA should therefore be used to transition from consumptive to non- or less-
968 consumptive means of enhancing human expression and wellbeing.

969 In general, any measures to protect more areas and concentrate development in areas that are already
970 disturbed warrant attention (e.g., Venier et al. 2014). New roads and development in previously remote
971 areas should be avoided, because opening up access causes chain reactions of effects (Cochrane and
972 Laurance 2008, Fraser 2014). Similarly, Bond's and co-authors (2012) rules about how to handle trade-
973 offs warrant implementation: an acceptable trade-off is defined as delivering net long-term
974 sustainability gains; no trade-off involving significant adverse effects is acceptable, and no displacement
975 of adverse impacts into the future is tolerable "unless all other alternatives are worse"; when a trade-off
976 is proposed, its justification is the onus of the proponent, and this justification must be reviewed in an
977 open participatory process, relative to established decision criteria. Ultimately planning and regulatory

³⁹ Precaution is used here in the legal sense, as a principle that "ensures that a substance or activity posing a threat to the environment is prevented from adversely affecting the environment, even if there is no conclusive scientific proof linking that particular substance or activity to environmental damage" (Cameron and Abouchar 1991).

instruments should include limits⁴⁰ (e.g., Johnson 2013) on population and developed land (Hegmann and Yarranton 2011) as a way to stimulate innovation and prevent the death by a thousand cuts.

Societies should better integrate CEA and planning (i.e., CEA should be viewed as both a tool for plan creation and evaluation), and should set clear targets for social/cultural, economic, and ecological indicators: Better consolidating CEA and planning would create a “vertically integrated framework” (Pope et al. 2013) in which environmental and sustainability issues could be considered with appropriate detail at appropriate levels of decision making. It could also benefit both processes by helping to clarify sustainability goals and uncovering (and putting to practical use) meaningful thresholds for important indicators of ecological and social well-being (Hegmann and Yarranton 2011). Articulating sustainability goals, and implementing them as regulatory limits (e.g., Johnson 2013) would lend administrative efficiency to CEA. This would alleviate the tendency for organizations to demand onerous appraisals as a way to compensate for inadequate policies and conflicting views of sustainability (Hegmann and Yarranton 2011). It would also greatly simplify evaluations of CEA performance. Furthermore, beneficial spin-offs outside of CEA would accrue, because targets remove ambiguity from well-intended but vague policy statements, which facilitates strategic planning and provides antecedents for complementary laws and regulations (Samhoury 2011).

Consider environmental appraisal and planning to be tools for managing change, not development.

Encouraging development where it makes sense to do so, and constraining it where unacceptable trade-

⁴⁰ Johnson (2013) defined *regulatory limit* as “the magnitude or extent of human disturbance that is permitted, after which unacceptable ecological change or risk is expected”.

998 offs are likely to result should be pursued to the extent possible (Hegmann and Yarranton 2011). The
 999 goal should be “qualitative rather than quantitative growth”⁴¹ (Hayha and Franzese 2014).
 1000
 1001 **If the chief purpose of CEA is to enforce evidence-based rationality, then formalize quantitative rules**
 1002 **in the decision making process.** Evidence-based decision making demands trade-offs to be defined and
 1003 revealed through a structured process (Johnson 2013), and targets are a critical part of this process.
 1004 Even a vague, qualitative target can stimulate policy debate and research concerning desirable and
 1005 undesirable end-points. Beyond this, evidence-based decision making can be formalized and quantified
 1006 by measuring indicator distances to the target (Moldan et al. 2012). Control charts (i.e., time-series
 1007 plots showing trends in VEC condition, relative to acceptable limits) should be hanging on boardroom
 1008 walls. Referring to such charts would help to enforce rationality by drawing decision-makers’ attention
 1009 to their own biases (e.g., Rubin and Kaivo-oja 1999), while promoting “futures-oriented thinking”
 1010 (Masini 1993), and focussing debate on trade-offs. By this method, human activities would be assessed
 1011 on a distance-to-target basis (e.g., Moldan et al. 2012) and approved if their predicted effects did not
 1012 exceed a pre-defined regulatory limit, which Johnson (2013) suggested could be set relative to models of
 1013 ecological response, socioeconomic trade-offs, and technological best practices. Johnson’s (2013)
 1014 uncertainty-based guidance illustrated how such control charts could be interpreted in relation to
 1015 “critical limits” (a point at which a VEC is nearing unacceptable change), “target limits” (which
 1016 operationalize an acceptable amount of VEC change, relative to ecological and socio-economic realities),

⁴¹This turn of phrase from Hayha and Franzese (2014) was made while contrasting flows of different types of capital in what they referred to as “strong” and “weak” systems of sustainability. Re-stating their comment, strong sustainability considers natural capital (local ecosystems, biomes, sub-soil resources) to be irreplaceable, whereas weak sustainability assumes that technological substitutes can be found for lost natural capital. Strongly sustainable (“qualitative”) development, then converts natural capital to manufactured capital (e.g., roads, buildings) so as to maximize positive spin-offs to human capital (e.g., knowledge), and social capital (institutional capacity); and this conversion of natural capital is constrained by its natural rate of regeneration. The Ecological Footprint concept of sustainability (i.e., Wackernagel and Rees 1998) takes a similar view, thus a city is sustainably developed so long as its footprint doesn’t exceed the area of biosphere required to produce its raw materials.

and “cautionary limits” (which identify ecological or socio-economic changes that require adaptive monitoring).

Maximize opportunities for deliberation in CEA, because its deliberative outcomes — which include and require debate, collaboration, creativity, learning, exposure to different world views, and consideration of the distribution of power among decision makers — have the greatest potential to revolutionize our approach to sustainability. Given damning critiques of the concept of rational information-based decision making, various authors have emphasized the need for “new thinking about planning and decision making processes in their wider social, cultural, political and economic contexts” (Morgan 2012). One of the major problems with the model of information-based decision making in CEA is that it subverts meaningful civic debate by disguising development options as being merely technical, rather than political. Unfortunately, no better model has come to light (Owens et al. 2004, Bond and Pope 2012): more political views of the decision-making process, for example, are called-out as being naive because their proponents expect a difficult, time consuming, expensive, and potentially inconclusive process of deliberation to result in clear recommendations and actions (Owens et al. 2004). Regardless, information-based appraisals, and appraisals that stress the deliberative process are not mutually exclusive, and providence calls for CEA to derive its knowledge-based products from a process that is as inclusive as possible, and seeks to maximize creativity and opportunities for collaboration and open dialogue among its participants (e.g., Bartlett and Kurian 1999, Adelle and Weiland 2012, Folkesson et al. 2013; Ball et al. 2013). Novel forms of “ad hoc deliberation” have been advocated as one promising approach to complement regulated consultation and boost deliberative outcomes (i.e., Folkesson et al. 2013).

1040 **Continue to reason through CEA's operational challenges, and update guidance documents where**
1041 **possible (Connelly 2011), as a way of ushering in a more enlightened CEA (Table 2).** Many operational
1042 challenges and shortcomings of CEA guidance documents arise because objective decision criteria (e.g.,
1043 in relation to scope, scale, and thresholds) are non-existent. The regional variability of CEA requirements
1044 is a further complication, because it precludes generalization. Regardless, there are still plenty of
1045 opportunities for innovation. Researching methods by which trade-offs can be optimized quantitatively
1046 may be a promising approach. For example, ways of optimizing spatial and temporal scale relative to the
1047 uncertainty and significance of effects would be helpful, as would procedures that align CEA's spatial
1048 boundaries with VECs (Baxter et al. 2001), and with the presumable geographic extent of stressors and
1049 effects" (Seitz et al. 2011, Ball et al. 2013).

1050
1051 **Improve monitoring systems.** Lack of data is a universal complaint among CEA practitioners. Regional
1052 monitoring programs that are interwoven with research agendas, planning and regulatory processes,
1053 and are supported with long-term funding, robust data-management, and data-sharing systems should
1054 be implemented widely (Ball et al. 2013, Dubé et al 2013). Such programs stand to benefit many
1055 elements of CEA, by characterizing baseline conditions, detecting and describing trends, permitting
1056 stressors and effects to be associated (Seitz et al. 2013), and enabling adaptive management
1057 (Karkkainen 2002).

1058
1059 **Consolidate good practices among EIA disciplines.** Returning to the basics with a re-focusing on better
1060 scoping and the sustainability ideal would inspire practitioners intellectually, and would uncover
1061 different ways of looking at the same problem, which would benefit EIA and all of its sub-disciplines
1062 (Canter et al. 2010, Sheate 2010, Morrison-Saunders et al. (2014).

1063

1064 **Continue to work on critical science questions.** In particular, continue to investigate and theorize how
1065 environmental appraisal and decision-making interrelate (Cashmore 2004, Bond and Pope 2012), and
1066 continue to elucidate links between stressors and effects, which will enhance our capacity for
1067 prediction.

1068

1069 **Foster interdisciplinarity among CEA researchers and their institutions.** Interdisciplinary study of CEA's
1070 role in socio-ecological systems is equally important as discipline-specific research (Leknes 2001,
1071 Cashmore 2004). EIA Researchers should establish interdisciplinary teams, governed by accountability
1072 and communication strategies that maximize reciprocal learning and define expected outcomes and
1073 timelines. Academic institutions should provide training and mentorship opportunities in
1074 interdisciplinary research (Morse et al. 2007).

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1503 **Personal Communications**

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1530 **Tables**

1531 Table 1: Hallmarks of enlightened CEA, relative to conventional impact assessment (adapted from Gunn
1532 and Noble 2009, and Noble 2010)

	Conventional impact assessment	Enlightened CEA
Questions¹	What are the likely additive or incremental effects of stressors associated with the alternative project(s)? Are these effects likely to be significant? Can effects be mitigated by altering project designs?	What are the potential cumulative effects associated with alternate future scenarios, relative to sustainability goals?
Planning perspective^{1,2,4}	Abundance; project planning and prioritization	Limits (finite biosphere); societal futures, especially concerning regional development and sustainability
Management perspective¹	Mitigating development impacts	Ensuring preferred societal outcomes; sustainability
Trigger^{1,2}	Effects of a project, or a collection of projects, on the environment immediately surrounding the projects	Contemplated changes or undertakings (especially where outcomes have potential to be at odds with sustainability)
Proponent^{1,2,3}	Developer, collective of developers, or sector advocate	Lead organization (often a regional planning authority) or cross-sector collaboration with sufficient mandate, finances, and capacity

Scope of stressors^{1,2}	Project stressors	All stressors
Temporal Bounds^{1,2,6}	Life cycles of past, present, and future projects	Long-term societal futures
Spatial bounds^{1,2,5}	Project(s) vicinity	Ecologically based, often watersheds, ecoregions, planning authority jurisdictions, or areas that encompass a series of related projects (existing and/or planned)
Criteria for evaluating effects^{1,2}	Ecological significance	Ecological significance; Significance relative to sustainability goals
Alternatives considered^{1,2,6}	Whether to proceed; whether modifications are required before proceeding	Alternative future scenarios
Rationale for monitoring^{1,2,7,8}	Project-based regulatory compliance; efficiency-based performance indicators common	Behooved by complexity and uncertainty (permits adaptation); promotes reciprocal learning between CEA and planning, particularly with respect to thresholds for judging the acceptability of effects and carrying capacity; performance assessed largely on the basis of effectiveness

¹Gunn and Noble (2009); ²Noble (2010); ³Sheelanere et al. 2013, ⁴Wackernagel and Rees (1998); ⁵Spaling et al. 2000; ⁶Duinker and Greig (2007); ⁷Walters (1986); ⁸Owens et al. (2004)

1536 Table 2: Core principles of CEA, and their logical soundness. The logical soundness of each principle is
1537 evaluated according to the degree of consistency or agreement among, and the completeness of, its
1538 supporting premises.

Theoretical element or operational principle	Logical status
(C1) To be sustainable, human enterprise must conform to the limitations of Earth’s biosphere, and CEA is an important tool for making this happen.	Inconsistent/incomplete: Although it has been entrenched globally into laws and regulations, CEA has resulted in little progress toward sustainability, and some authors have argued it has been counter-productive (e.g., Duinker and Greig 2006). Furthermore, disagreement about precisely what CEA is supposed to achieve make its performance difficult to assess unequivocally.
(C2) Cumulative effects are aggregated, collective, accruing, and/or combined ecosystem changes that result from a combination of human activities and natural processes; however they are commonly defined in a more restrictive sense in policies, laws, and regulations — for example, as effects of an undertaking and its interaction with other activities occurring at the same time and in the same area.	Inconsistent/complete: The chief inconsistency concerns the definition of <i>effect</i> , which can be argued either as purely biophysical, or as including a socio-cultural dimension.
(C3) Cumulative effects assessment is a sub-discipline of EIA; it is “the process of	consistent/complete

predicting the consequences of development, relative to an assessment of existing environmental quality”, or “the process of systematically analyzing cumulative environmental change”. It is a systematic way to evaluate the significance of effects from multiple activities and to inform resource managers about these effects. Local differences in methods exist, and are necessitated by region-specific laws, policies, regulations, and planning systems.

(C4) CEA has multiple objectives, which are loosely arranged around the themes of formalizing environmental values, establishing an ecologically viable socio-economy, and improving knowledge and governance. As a form of environmental appraisal, CEA is not just a tool for informing and influencing decision-makers. It also changes the views and attitudes of its participants, and its influence can propagate outward through participants’ social networks to influence entire institutions.

Inconsistent/incomplete: Evidence about precisely what CEA is supposed to achieve is incomplete and contradictory.

(C5) VECs are used to provide a tractable

Inconsistent/incomplete: Controversy exists about

scope for CEA, and to ensure that attention is paid to “the most important environmental features and processes”.	whether the concept of a VEC, as significant ecological feature, should be more broadly defined as elements of sustainability or societal progress; objective criteria for determining which VECs ought to be included in a given CEA are lacking)
(C6) In principle, biological (effect-based) indicators are superior to stressor-based indicators for CEA. In practice, if ecological effects are detected, the stressors causing the effects must typically be identified; therefore both indicator types may be required to diagnose causes of, and model, ecosystem changes.	Consistent/complete
(C7) Consensus on CEA’s operational steps has been reached; however objective criteria for guiding decisions that must be made at each step are lacking, and a degree of pluralism is permitted so each CEA is tailored to its context. CEA practice falls short of the aspirational ideal.	Consistent/complete: To avoid confusion, note that this well supported claim argues that inconsistencies in operational methods exist, largely because no objective guidance can be given about the particular scope, scale and significance thresholds to use in any given CEA; furthermore, it argues that CEA implementation has fallen short of expectations, particularly as regards the exploration of development alternatives, use of scenario-based predictive models as futuring tools, and monitoring effectiveness of the CEA process itself.

(C8) Monitoring and adaptive management Consistent/complete

are essential to CEA.

(C9) Public involvement is essential, regardless Consistent/complete

of how one considers CEA's value to partition among information-delivery and deliberative outcomes.

(C10) Continued enlightenment and endorsement of CEA requires its efficacy and efficiency to be assessed. Consistent/complete (but note that efficacy is difficult to evaluate because of disagreements about precisely what outcomes CEA ought to bring about; and it remains unclear how to implement evaluative frameworks that have been proposed)

(C11) Basic knowledge about ecological stressors and effects is rudimentary. Consistent/complete: The most significant problems with CEA are not scientific.

Nonetheless, numerical methods for quantifying, assessing, modeling, and predicting cumulative effects are well described. On one hand, our capacity for prediction is often small, and there are practical limits to the number of factors that can be tested experimentally or modelled; on the other hand, crude approximation of cumulative effects is sufficient in most CEA contexts.

(C12) CEA is best undertaken in a strategic and Consistent/complete:

regional context, but there are few examples of this in current practice.

(C13) CEA and planning are inseparably linked, and communication between these disciplines allows for reciprocal learning.	Consistent/incomplete: The full case for integrating CEA and planning has not yet been compiled. To avoid confusion, note that the logical case for merging CEA and planning is consistent; however examples of this marriage from current practice are rudimentary, in part because of institutional and jurisdictional mismatches and inertia.
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