Session 75

Prevention, assessment, and mitigation of coral reef impacts resulting from planned and unplanned human activities

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The biological condition gradient, a tool used for describing the condition of US coral reef ecosystems

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Abstract Understanding the effects of human activity on coral reef ecosystems requires knowing what characteristics constitute a high quality coral reef and identifying measurable criteria. The Biological Condition Gradient (BCG) is a conceptual model that describes how biological attributes of coral reefs change along a gradient of anthropogenic stress. The BCG provides a framework using qualitative and quantitative reef attributes to determine current coral reef conditions. Experts in coral reef assemblages (coral, fish, sponge, gorgonian, and algae) have defined a BCG model for Puerto Rico. The model describes the full range of biological conditions resulting from human disturbance, including community structure, organism condition, ecosystem function and connectivity. Each condition level is defined in terms of biological integrity, which is the biological condition comparable to undisturbed or minimally disturbed conditions caused by human influence. Each level contains a detailed narrative and decision rules for translating the narrative into specific metric scores. Reference condition is a natural fully-functioning coral reef that serves as a non-shifting baseline that is established through expert consensus. Managers can use the BCG model to assess current conditions relative to high quality coral reefs, track changes in condition as responses to management actions, and communicate environmental condition and outcomes to the public. BCG levels can be aligned with designated aquatic life uses specified in water quality standards and used for protection and potential restoration of coral reefs. The BCG model will be broadly applicable to Caribbean reefs, and the process is transferable to other oceanic regions.

Key Words: biological condition gradient, biological criteria, biocriteria, protection coral reefs, Clean Water Act, thresholds

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Introduction

One of the most influential legal mechanisms available for aquatic resource protection is the U.S. Clean Water Act (CWA) (33 U.S.C. 1251 et seq. 1972), which grants regulatory authorities to the U.S. Environmental Protection Agency (USEPA) to protect the integrity of the Nation's waters (USEPA 2016). The CWA purview includes biological components such as coral reefs that lie within the limit of the territorial seas (Jameson et al. 2001). One authority granted to USEPA is to prevent waterbody degradation or restore habitat quality through the CWA Section 101 (a) (Frey 1977; USEPA 2002). This authority allows decisions to curtail or modify deleterious anthropogenic activities "to restore and maintain the chemical, physical and biological integrity of the nation's waters." Many facets of the CWA are already employed in maintaining high water quality imperative for coral reef persistence (USEPA 2016). However, the broad authority of the CWA is not being used to its full potential for reef protection (Fore et al. 2009; Bradley et al. 2010).

Understanding the effects of human activity on coral reefs requires knowing what attributes constitute high quality coral reefs and identifying measurable criteria. Restoring and maintaining biological integrity is a long-term CWA objective, and like its physical and chemical counterparts, biological criteria can be defined to protect valued biological communities (Davies and Jackson 2006). Biological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to the natural habitats within a region (Karr and Dudley 1981). The process includes classifying habitat types, using quantitative measures of species composition, diversity and functional organization; and comparing existing waterbody condition to natural or undisturbed reference conditions (Davis and Simon 2004).

To achieve CWA objectives, the USEPA, States, US Territories, regulated industries, municipalities, and public need comprehensive information about the biological integrity of aquatic environments to complement the physical and chemical integrity. The USEPA has worked with scientists to adapt a conceptual model known as the biological condition gradient (BCG) to protect the biological integrity of tropical Caribbean waters, including marine coastal habitats such as mangroves, seagrasses and coral reefs (Bradley et al. 2014; Bradley and Santavy

2016). The BCG is a conceptual model that describes how biological attributes of coral reefs change along a gradient of anthropogenic stress (Figure 1). The BCG relates the biological responses to increasing levels of anthropogenic stress relative to a baseline anchored in natural condition or minimally disturbed (Karr 1991; Davies and Jackson 2006; USEPA 2016). This framework defines qualitative and quantitative reef attributes to assess the biological condition and ecological state of a coral reef by defining multiple levels of biological responses to increasing anthropogenic stress. BCG level 1 represents the highest condition level or full biological integrity with ideally no anthropogenic stress, and BCG level 6 represents the poorest biological condition impacted by the greatest anthropogenic stress (Fig. 1). Threshold levels can be both numeric values and narrative descriptions dependent on the scientific information available, and they are intended to be protective of the biological integrity of aquatic life inhabiting the waterbody. The BCG model provides guidance to decide whether the biological condition of a coral reef is improving or declining relative to these acceptable threshold levels.

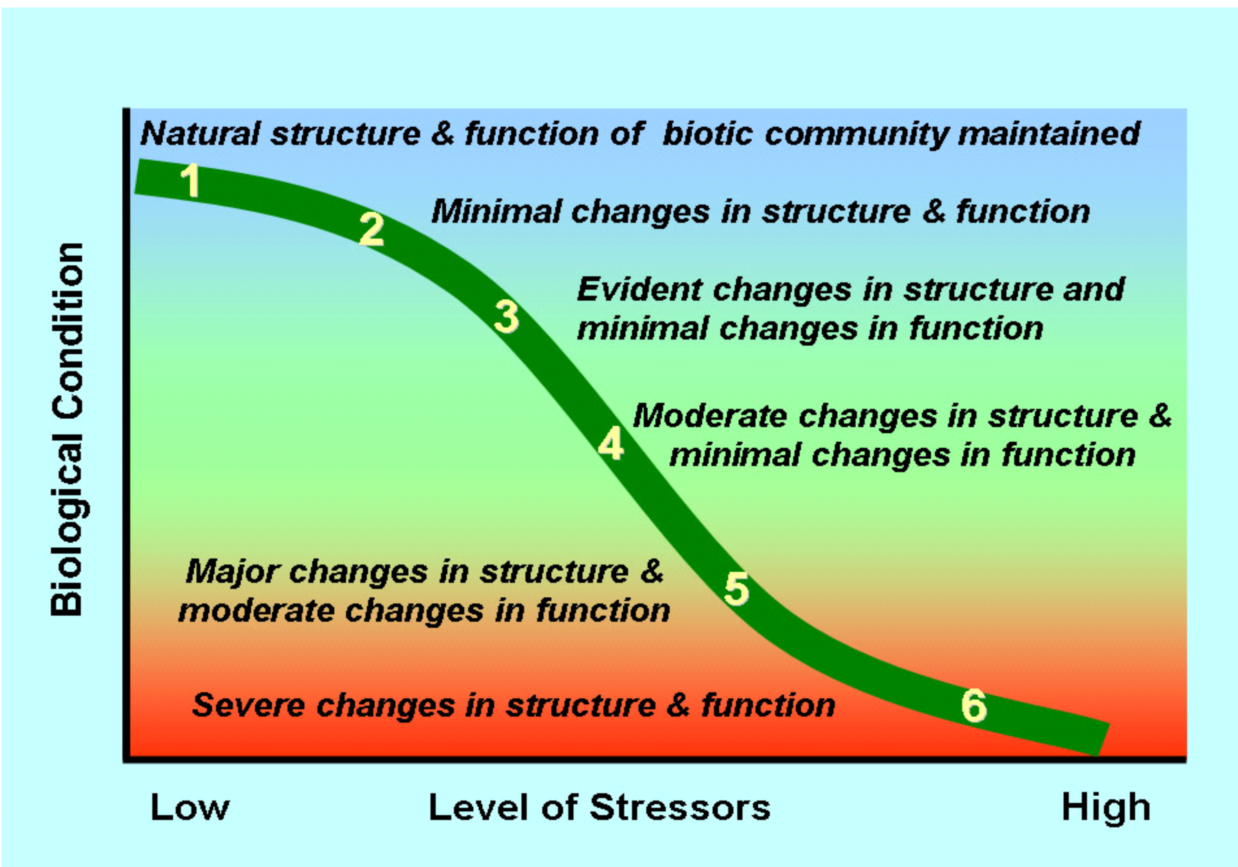

Fig. 1 Conceptual model of the biological condition gradient that describes how biological attributes of coral reefs change along a gradient of anthropogenic stress

The BCG framework allows biological condition to be interpreted independent of assessment methods. Currently, the BCG is used nationally for the management of freshwater ecosystems to communicate to the public and other interested stakeholders the status of aquatic resources and their potential for restoration. To date, almost all applications are in freshwater streams, rivers, and lakes bounded by land. A BCG model is formulated based on expert consensus using best professional judgment. An expert panel works together to define the thresholds at each biological condition level using narrative descriptions. Next, numeric thresholds are developed using bioassessment data to calculate threshold values grounded in the early narrative formulations. Application of the BCG conceptual framework, narrative descriptions developed by experts for qualitative rankings, habitat classifications, and assignment of important reef attributes are presented for fish and coral models.

Materials and methods

USEPA focused on southwestern Puerto Rico to test proof-of-concept, develop, calibrate, and eventually validate the BCG model to support biocriteria development for Caribbean coral reef systems. An expert panel of coral reef scientists participated in three workshops and multiple webinars to elicit best professional judgment to develop narrative and ultimately numeric biocriteria to define multiple BCG condition levels (Bradley et al 2014; Bradley and Santavy 2016). In the first workshop, underwater videos and photographs were viewed by experts to elicit important coral reef attributes to define coral reef condition. This approach allowed experts to draw on their individual and combined knowledge and expertise, without getting mired in CWA and biocriteria concepts and terminology. Linear coral reefs were selected from habitat maps by Kendall et al. 2001. Sites selected for expert review spanned the full range of conditions observed in the data set. Experts rated coral reef condition for 12 stations as either good, fair or poor based on the photos and videos considering all aspects of reef condition and health. They were instructed to document specific characteristics indicative of conditions for corals, sponges, gorgonians, fish, algae, reef rugosity, and topographical heterogeneity. Afterwards, group deliberations used their individual evaluations to focus on identifying common attributes with narrative language to differentiate each level.

During the second and third workshops, two separate BCG models were constructed independently - one for fish communities built by fish experts and the other for scleractinian corals built by coral experts. Each group worked from the narrative descriptive BCG model developed in the first workshop with the ultimate goal of creating a quantitative model with decision rules for threshold levels. Bioassessment data for fish and coral communities were used with sites located along a stressor gradient ranging from low to high land-based stressor levels in similar habitat types for each community (Santavy et al. 2012; Bradley and Santavy 2016). Ideally, data should include the full range of conditions and complement of stressors (e.g., pollution sources, fishing pressure, habitat disturbances, etc.) found at the regional level, such that the full gradient of the responses of the assemblages were included in model development. Since natural, regional, and habitat characteristics affect coral species composition of undisturbed waterbodies, a critical step required habitat classification of natural conditions to the extent they affect structures of fish and benthic communities (USEPA 2016).

The first step for BCG calibration was assigning taxa to BCG attributes I-V (Table 1), based on species sensitivity and tolerances to the most important stressors recommended by the experts. The BCG attribute definitions were those developed for freshwater systems (Table 1). Each taxon was evaluated for: sensitivity and tolerance to anthropogenic stressors, rarity, and endemism (Davies and Jackson; 2006; USEPA 2016). Experts assigned all fish and scleractinian coral taxa present in Puerto Rican bioassessment data from USEPA surveys in 2010 and 2011

Table 1 Ecological attributes used in freshwater BCGs for fish and benthic infauna communities (USEPA 2016)

Attribute	Description
I	Historically documented, sensitive, long-lived or regionally endemic taxa
II	Highly sensitive taxa
III	Intermediate sensitive taxa
IV	Taxa of intermediate tolerance
V	Tolerant taxa
VI	Non-native species
VII	Organism condition
VIII	Ecosystem function
IX	Spatial and temporal extent of detrimental effects
X	Ecosystem connectivity

(Bradley and Santavy 2016). Next, experts assigned BCG biological condition levels (1-6) to each reef site using results from the more complex data-driven analyses and the BCG attribute (I-V) assignments. As more sites were assigned to BCG condition levels, the experts were providing more complex data-driven analyses for improving and informing their judgements to rate additional sites. After condition assignments were made to multiple sites which represented a range of anthropogenic stressors, the experts' rationale for their assignments were carefully documented. This allowed decision rules to emerge for distinguishing different quantitative BCG levels.

Results and Discussion

The first workshop provided proof of concept that the BCG framework could be adapted for coral reef ecosystems (Bradley et al. 2014). During the first workshop, the coral reef experts collectively developed preliminary narratives for defining four BCG condition levels ranging from very good to excellent, good, fair, and poor (Fig. 2) while documenting specific attributes. Using underwater videos, the experts defined eight individual traits into four levels of biological condition. They rated the first level as very good to excellent condition, representing full biological integrity, and it anchored the other condition levels. This condition level was considered by the experts as comparable to levels 1 and 2 of the BCG conceptual model. The second level was considered good condition by the experts as comparable to BCG Level 3. The third level was rated as fair condition and comparable to BCG level 4. The worst condition level was comparable to BCG levels 5 and 6 and considered to be highly degraded.

The experts identified eight narrative attributes used for describing each BCG level. The narrative attributes were: physical structure of the reef which is the topographical heterogeneity, roughness or rugosity of the reef surface; coral characteristics including species, shape, size, and population demographics; sponge and gorgonian characteristics of shape, size and potential for habitat provision; coral condition which is considered the amount of live tissue present and extent of disease, bleaching and tumors; fish abundance, biomass and trophic interactions; the presence of other vertebrates focusing on charismatic megafauna; selected invertebrates including *Diadema antillarum*, conchs, lobsters, and crabs; and finally algae ranging from calcareous crustose and coralline algae, filamentous microalgae, to fleshy turf algae; and submerged aquatic vegetation.

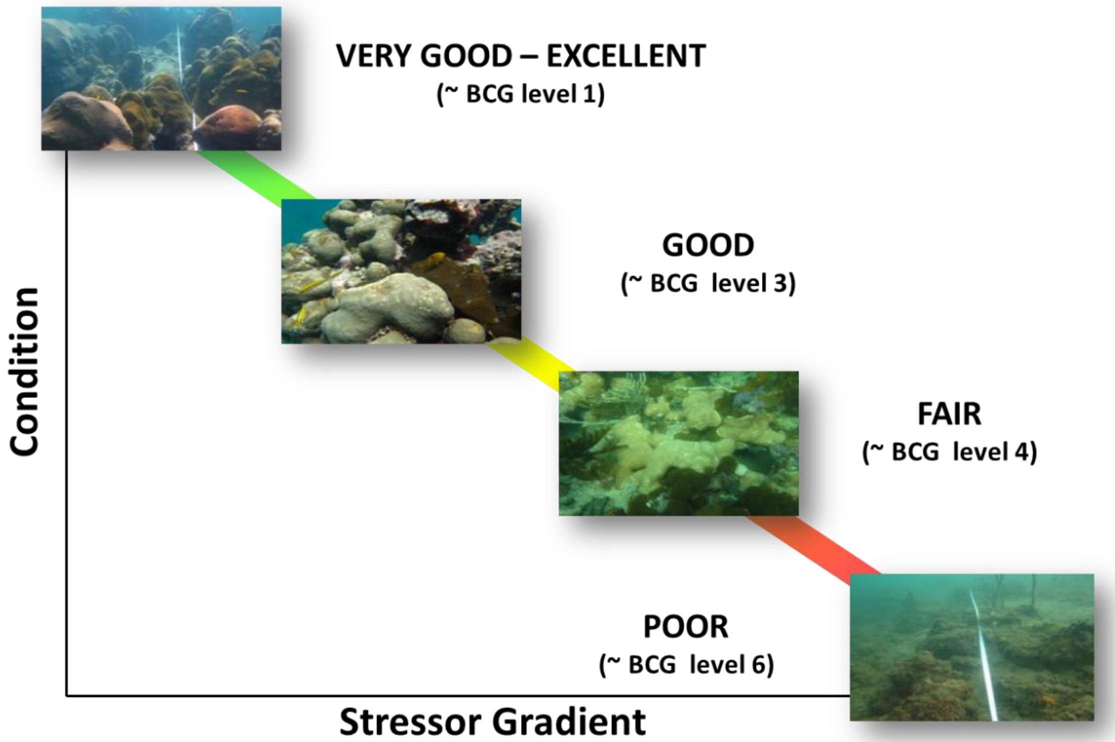

Fig. 2 Conceptual BCG developed during the 1st workshop, using site photos to represent BCG levels in Puerto Rico. Experts agreed natural site equivalent to BCG level 1 is not present in Puerto Rico today

The experts used these eight attributes to describe four coral reef condition levels (Table 2). The best biological condition was grounded in natural, undisturbed condition, represented by high rugosity and species diversity; large colonies of *Orbicella* spp. with high tissue coverage; and balanced population structure that included more corals than gorgonians. The highest quality communities contained large autotrophic and highly sensitive sponge species and low prevalence of disease or tumors in benthic communities. Crustose coralline algae were abundant, and other invertebrates were present (lobster, small crustaceans, and polychaetes), with some large sensitive anemone species. The worst condition had low structure and rugosity, turbid water and sediment films. If coral colonies were present, they were small and highly tolerant species. Heterotrophic, tolerant sponges were buried in sediment. Sediment-dwelling organisms such as polychaetes and holothurians dominated the substrate with few or no reef invertebrates. If algae were present, it was fleshy macroalgae, with little or no turf or calcareous algae. Crustose coralline algae were absent.

Table 2 Narrative descriptions for eight attributes proposed by coral reef experts to define four BCG condition levels for Puerto Rico linear reefs. (adapted from Davies and Jackson, 2006)

Condition level	Attribute descriptions
Very Good Excellent (approximate BCG Level 1–2)	**Physical structure:** High rugosity or 3D structure; substantial reef built above bedrock; many irregular surfaces provide habitat for fish; very clear water; no sediment, flocs or films
	Corals: High species diversity including rare; large old colonies (*Orbicella*) with high tissue coverage; balanced population structure (old and middle-sized colonies, recruits); *Acropora* thickets present
	Gorgonians: Gorgonians present but subdominant to corals
	Sponges: Large autotrophic and highly sensitive sponges abundant
	Fish: Populations have balanced species abundances, sizes and trophic interactions
	Large vertebrates: Large, long-lived species present and diverse (turtles, eels, sharks)
	Other invertebrates: *Diadema*, lobster, small crustaceans and polychaetes abundant; some large sensitive anemone species present
	Algae: Crustose coralline algae abundant; turf algae present but cropped and grazed by *Diadema* and herbivorous fish; low abundance of fleshy algae
	Condition: Low prevalence of disease and tumors; mostly live tissue on colonies
Good (approximate BCG Level 3)	**Physical structure:** Moderate to high rugosity; moderate reef built above bedrock; some irregular cover for fish habitat; water slightly turbid; low sediment, flocs or films on substrate
	Corals: Moderate coral diversity; large old colonies (*Orbicella*) with some tissue loss; varied population structure (usually old colonies, few middle aged and some recruits); *Acropora* thickets may be present; rare species absent
	Gorgonians: Gorgonians more abundant than Levels 1–2
	Sponges: Autotrophic species present but highly sensitive species missing
	Fish: Decline of large apex predators (e.g., groupers, snappers) noticeable; small reef fishes more abundant
	Large vertebrates: Large, long-lived species locally extirpated (turtles, eels)
	Other invertebrates: *Diadema*, lobster, small crustaceans and polychaetes less abundant than Levels 1–2; large sensitive anemone species absent
	Algae: Crustose coralline algae present but fewer than Levels 1–2; turf algae present and longer, more fleshy algae present than Levels 1–2
	Condition: Disease and tumor presence slightly above background level; more colonies have irregular tissue loss
Fair (approximate	**Physical structure:** Low rugosity; limited reef built above bedrock; erosion of reef structure obvious; water turbid; more sediment accumulation, flocs and films; *Acropora* usually gone or present as rubble for recruitment substrate

BCG Level 4)	**Corals:** Reduced coral diversity; emergence of tolerant species, few or no living large old colonies (*Orbicella*); *Acropora* thickets gone, large remnants mostly dead with long uncropped turf algae
	Gorgonians: Gorgonians more abundant than Levels 1–3, replacing sensitive coral and sponge species
	Sponges: Mostly heterotrophic tolerant species and clionids
	Fish: Absence of small reef fishes (mostly Damselfish remain)
	Large vertebrates: Large, long-lived species locally extirpated (turtles, eels)
	Other invertebrates: *Diadema* absent; *Palythoa* overgrowing corals; crustaceans, polychaetes and sensitive anemones conspicuously absent
	Algae: Some coralline algae present but no crustose algae; turf is uncropped, covered in sediment; abundant fleshy algae (e.g., *Dictyota*) with high diversity
	Condition: High evidence of diseased corals, sponges, gorgonians; evidence high of mortality; usually less tissue than dead portions on colonies
Poor **(approximat e BCG Level 6)**	**Physical structure:** Very low rugosity; no or little reef built above bedrock; no or low relief for fish habitat; very turbid water; thick sediment film and thick floc covering bottom; no substrate for recruits
	Corals: Absence of colonies, those present are small; only highly tolerant species with little or no live tissue
	Gorgonians: Small and sparse colonies; mostly small sea fans; often diseased
	Sponges: Heterotrophic sponges buried deep in sediment; highly tolerant species
	Fish: No large fishes; only a few tolerant species remain; lack of multiple trophic levels
	Large vertebrates: Usually devoid of vertebrates other than fishes
	Other invertebrates: Few or no reef invertebrates; high abundance of sediment dwelling organisms such as polychaetes and holothurians
	Algae: High cover of fleshy algae (*Dictyota)*; complete absence of crustose coralline algae
	Condition: High incidence of disease and low or no tissue coverage on small colonies of corals, sponges and gorgonians, if present

During the second and third workshop, the fish and coral experts worked on two separate BCG models. Development of the coral reef fish BCG model was more adaptable to the freshwater systems framework. Fish experts agreed upon two habitat classifications - sites containing coral reefs and all other hard-bottom habitats. Fish experts considered land-based sedimentation and fishing pressure as the two greatest threats to fish communities in this region, and they assigned 138 fish species to the five BCG attributes. The results from these assignments are too numerous to present here, but they are detailed in Bradley and Santavy 2016. The fish experts will be testing numeric criteria soon to test the fish BCG model for coral reefs to set preliminary model conditions for developing biocriteria for Puerto Rico.

The application of the freshwater BCG tolerance attributes to coral taxa presented a much greater challenge. The coral experts agreed elevated sea temperature and land-based sources of pollution present the most serious threats for Caribbean scleractinian corals. Coral experts had lower confidence in scleractinian coral taxa assignments to BCG attributes I-V and chose to evaluate each taxon for each stressor separately (Bradley and Santavy 2016). During initial attempts to assign species to a BCG attribute, the coral experts contended with reef habitat classification. They held discussions focused on defining expectations of which coral species should be found in different reef zones. Many reef traits were considered because reefs have distinct horizontal and vertical zones created by differences in depth, wave and current energy, temperature, light, and many other habitat characteristics (Zitello et al. 2009). The experts considered several different reef classification systems in an attempt to incorporate most of the critical reef traits discussed (Adey and Burke 1976; Hubbard et al. 2009). They agreed to use the latest edition of NOAA's benthic habitat reef classification as guidance (Zitello et al. 2009), and only use the fore-reef zone for assigning sites to BCG condition levels using the Costa et al. 2013 definition.

The coral experts decided the stressor tolerance attributes (I–V) developed for the freshwater BCGs (Table 1), did not apply very well to coral reef benthic communities. The experts believed tolerances of scleractinian coral species varied based on the individual stressor, and when exposed to multiple stressors the effects could be additive, neutral or synergistic but are largely unknown. The coral experts ultimately recommended focusing on eight narrative attributes developed during the first workshop (Table 2) to assign sites to BCG condition levels. The coral experts all agreed additional benthic assemblages rather than just scleractinian corals should be used. They changed the coral BCG to the benthic BCG model, and recommended inclusion of sponges, gorgonians, algae, organism condition especially disease and coral bleaching, and other reef invertebrates.

Historically water quality management programs and regulatory agencies attempted to protect aquatic life primarily through chemical and physical water criteria alone (USEPA 2002, 2016). Unlike chemical or physical criteria, biocriteria do not require individual threshold values for each and every stressor. The biological response to its environment integrates cumulative impacts of multiple stressors which might be better indicators of ecosystem condition, rather than only relying on established nutrient or physical stressor limits, which might not be protective of sensitive coral reefs (Bradley et al. 2010; Oliver et al. herein). Coral reef biocriteria are used to benchmark biological conditions required for aquatic life use, and allow bioassessment information to directly link management actions to desired biological goals and endpoints. Often the consequences of management decisions are far-reaching influencing not only inland watersheds but also coastal environments (Bradley et al. 2010).

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