Watershed Management and 'Ecotonal Networks'. A Holistic Approach to Coastal Management

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ABSTRACT   For the first time in the history of our species, the opportunity of halting the expansion of our global population discloses future scenarios of stably coexisting urbanised and non-urbanised ecosystems. The need for the establishment of such scenarios is particularly urgent in tropical regions, whose higher biodiversity is being rapidly eroded by recent and explosive urbanisation and land conversion. It is here proposed that the sustainable management of networks of urbanised and non-urbanised systems, the latter ones being interconnected by transitional systems, or ecotones, is the key to manage increasingly fragmented and isolated natural systems. In a cybernetic perspective, a decrease in internal connectivity both modifies fluxes with the external environment and impairs negative feedbacks, thus decreasing ecosystems' resilience. In particular, conservation efforts focused on traditionally conceived ecosystems have shown to be inappropriate to efficiently manage and protect tropical coastal systems. All these 'systems', although being anthropomorphically perceived as separate, evolved as deeply interconnected networks. The increasing loss of biocomplexity and resilience faced by such networks, is the inevitable consequence of the loss of internal connectivity determined by the loss of ecotones, due to fragmentation, degradation, and anthropogenic impact acting on the periphery of isolated natural areas. In order to sustainably manage natural isolated systems surrounded by urban, agricultural or degraded systems, appropriate management of ecological inputs and outputs, and maintenance of internal connectivity should be urgently implemented. Ecosystem-based management offers a rational perspective: (i) maximising the diversity of the managed systems within the original landscape, and (ii) creating and managing a dynamic network of ecotonal connections maintaining fluxes of energy and matter between them (Ecotonal NeTworks, or ENTs). Being inherently more resilient, such managed networks of natural subsystems would provide more sustainable and richer economic and ecological services, allowing for a rational integration of the highly interconnected urban subsystems.

(**Keywords:** conservation, ecosystem management, resilience, sustainability, coastal management)

INTRODUCTION

Human population growth and expansion of the human spatial niche is the ultimate cause of the global ecological changes that occurred in the recent history of our planet. In the last 10,000 years the human population increased from about 1-10 million to the present 7.0 billion, and is expected to reach 9.0 billion by 2044 (U.S. Census Bureau 2012, 2011a). In particular, one third of the world's human population lives in coastal areas and small islands, which constitute only 4% of the land area (Barbier et al. 2008).

Estimates of the earth's carrying capacity had been widely fluctuating since the 17th century, ranging from 10^9 to 10^{12} (Cohen 1995), with a median value of approximately 10^{10} people (UN 2001).

The number of recorded threatened species per country (IUCN 2011) might be used as an index of the global ecological changes induced by the expansion of human habitats. In fact, there is a significant and positive correlation between the number of threatened species and human population density (**Fig. 1**).

In particular, the number of threatened species is also significantly and positively correlated with relative coastline lengths, consistent with the high concentration of human presence in coastal systems (**Fig. 2**).

It is known that oceanic islands, that also have relatively longer coastlines per unit area, are rich in endemic
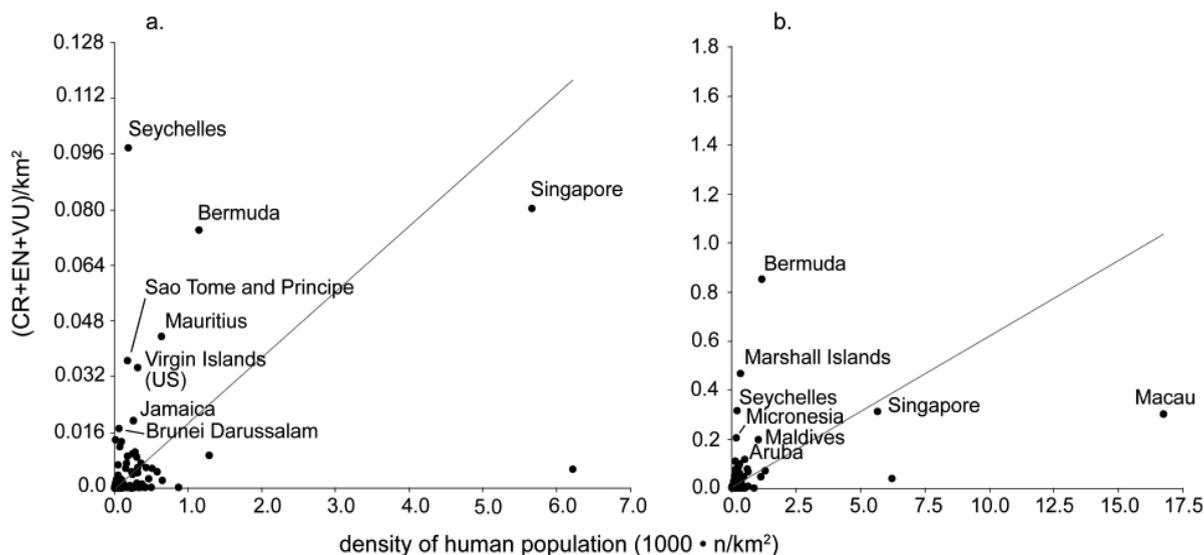
Figure 1. Number of Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) plant (a) and animal (b) species per km^2, versus human population density (number of individuals per km^2). Pearson's correlation coefficients = 0.41 (a) and 0.67 (b) ($p < 0.0001$ in both cases). RMA regression lines in red (PAST 2.8©; Hammer et al. 2001; Hammer & Harper 2005). Significant linear correlations between human population density and the sum of all the plant and animal species in IUCN categories (except Data Deficient species: DD) were also found (graphs not shown). Data on species from IUCN (2011). Data of land area and human population of countries from FAO (2011), UNSD (2008), FCO (2011), CIA (2011), CBS (2011), INSEE (2011), and Commonwealth Secretariat (2011).
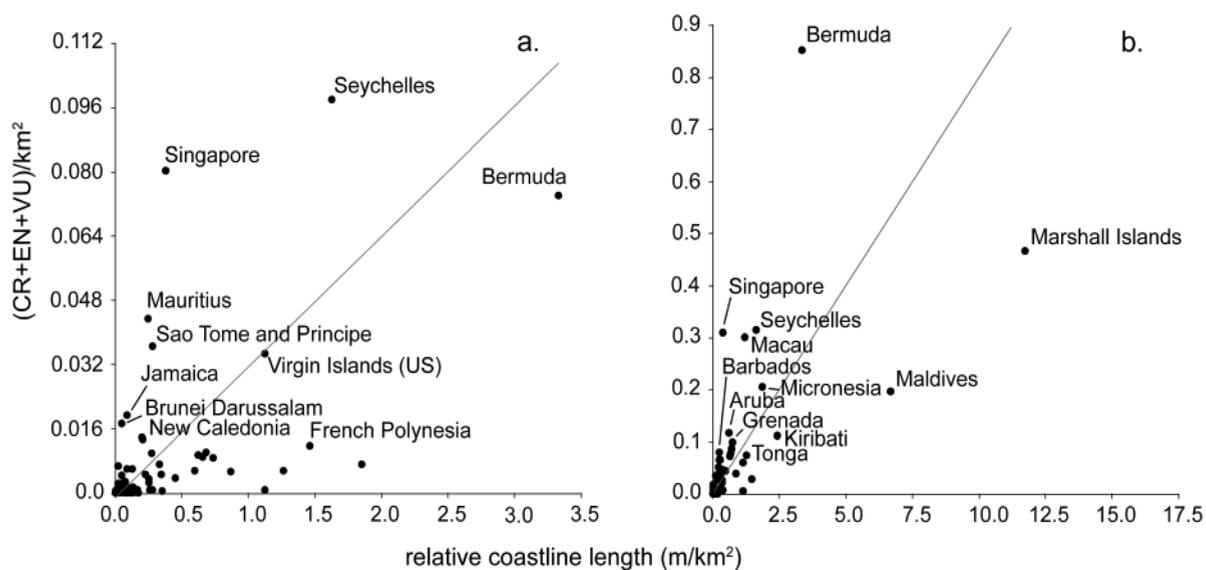

Figure 2. Number of Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) plant (a) and animal (b) species per km^2, versus coastline length relative to land area (m/km^2). Countries with higher numbers of threatened species are islands or small coastal countries, with relatively longer coastlines. Pearson's correlation coefficients = 0.63 (a) and 0.67 (b) ($p < 0.001$ in both cases). Significant and positive correlations between relative coastline lengths and either Extinct (EX) plus Extinct in the Wild (EW) plant and animal species, or all the IUCN species (except Data Deficient species: DD) were also found (graphs not shown). Relative coastline lengths were estimated by Pruett & Cimino (2000) based on the World Vector Shoreline database at 1:250 000 km, United States Defense Mapping Agency, 1989. Other data sources as in Fig. 1. Countries with missing data were eliminated from the dataset.

species and host relatively small populations (Whittaker & Fernández-Palacios 2007) that are more susceptible to anthropogenic impact (Kier et al. 2009) and have a large effect on global patterns of extinction (Pimm et al. 1995). Nonetheless, when countries including oceanic islands were eliminated from the dataset, correlations between relative coastal length and the number of recorded threatened species were still statistically significant (p < 0.001; *r* = 0.66 for animals; and 0.44 for plants, respectively; graphs not shown), suggesting that coastal areas are indeed focal stages where global patterns of extinction are driven by anthropogenic impact.

In the last 50 years, the ongoing global mass extinction (Pimm et al. 1995; Sepkoski 1998; Wilson 2002; Thomas et al. 2004; Lawton & May 2005; Kirch 2005; Lyons et al. 2005, Eldredge 2010), has been fostered by the industrial development and urbanisation of tropical regions. Tropical ecosystems host the great majority of

species on earth, and anthropogenic losses of biological and ecological diversity occur at higher rates than in temperate areas (Wilson 2002). As urban systems and human populations become increasingly connected, natural systems gradually shrink and disconnect one from each other (**Fig. 3**; Crooks & Sanjayan 2006). Non-urbanised ecosystems are physically surrounded by encroaching urbanised, agricultural and variously degraded ecosystems.

It is evident that the structure and functions of many 'conserved natural areas' are gradually changing due to habitat fragmentation, genetic erosion, and various forms of degradation. At the same time, while efforts were focused on traditionally conceived ecosystems (e.g. forests, lakes, rivers, etc.), transitional systems, or ecotones, which originally connected them are rapidly disappearing, both due to the fragmentation, and edge effects at the periphery of these ecosystems.
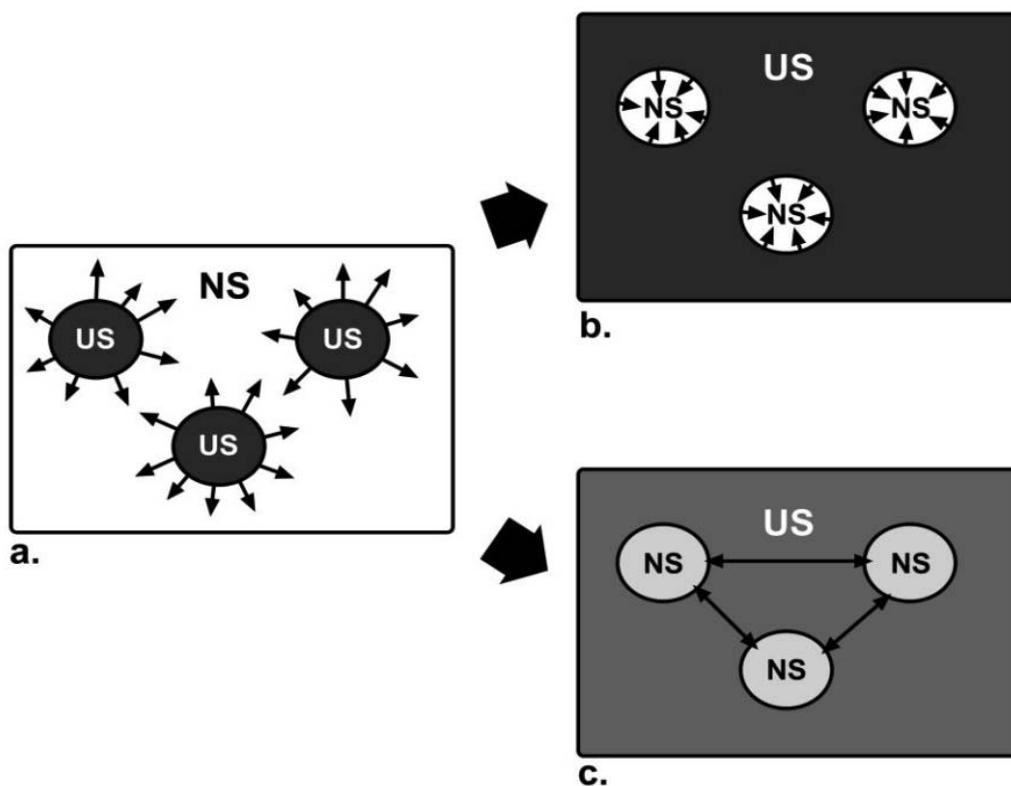

Figure 3.   From a condition (a) where 'natural' ecosystems (NS) are the external environment of largely isolated and expanding urban and agricultural systems (US), more and more areas on earth passed to a condition (b) where US is the external environment of isolated and shrinking NS. A hypothetical ecosystem-based management scenario (c) would encompass natural and urban systems reciprocally stabilised by networks of interactions. Ellipses and rectangles = diagrammatic representation of the ecosystems' area and their external environment, respectively; single arrows = direction of the spatial change of the subsystems; double arrows = ecological connections between NS. For more clarity, the ecological connections between NS and US were not illustrated.

However, if the global human population is still growing, and will probably continue to grow for the next decades, its percentage growth rate has been decreasing since the 1960s, from above 2% per year to about half this level, and is predicted to fall below 0.5% per year between 2040 and 2050 (U.S. Census Bureau 2011b). In this view, the possibility of halting the human population expansion discloses future scenarios of coexisting urbanised and non-urbanised worlds.

The following questions are here discussed: (i) Are the traditional concepts of 'protected areas' and 'conservation' sufficient to warrant the sustainability of non-urbanised systems? (ii) Does ecological theory point at alternative or complementary strategies, promoting the establishment of dynamic equilibria between urbanised and non-urbanised systems, thus optimising long-term ecosystem management? (iii) How such strategies can be applied to coastal management?

DISCUSSION

The conservationist utopia, dynamically homeostatic systems and the role of internal connectivity

The structure and function of an ecosystem is determined by fluxes of matter and energy from and to the external environment, and of positive and negative feedbacks, accounting for its resistance, resilience, and homeostasis (Odum & Barrett 2005). Ecosystems are also complex self-organising systems (Érdi 2008; Michener et al. 2001), and as McCann et al. (1998) demonstrated, a decrease in internal connectivity, such as a decrease of the diversity of fluxes between different functional patches (e.g. of trophic interactions between different species in a food web) results in the impairment of the attractors which bound oscillations away from extreme states (Kay et al. 1999). Extinctions of components of a biological system (e.g. species) is a typical form of extreme oscillation, which often implies loss of organisational biocomplexity and decreased resilience (Holling & Gunderson 2002). Consistent losses of internal connectivity or durable alteration of these fluxes overcoming thresholds of resistance will inevitably increase the probability of change (e.g. loss of biodiversity, degradation of ecological functions, etc.).

In a cybernetic perspective, a decrease in internal connectivity would both modify fluxes with the external environment, and negative feedbacks, thus decreasing the resilience of the system. Therefore, in order to 'conserve' natural isolated systems surrounded by urban or agricultural systems, both an appropriate management of ecological inputs and outputs, and the maintenance of internal connectivity should be implemented, in an ecosystem-based management perspective (Fig. 3c).

The goals of the sustainable management and conservation of natural systems cannot be achieved without the acknowledgement of the fundamental ecological and evolutionary continuity between them. In fact, networks of ecological connections naturally connect all terrestrial and aquatic ecosystems at both the landscape and seascape level.

Coastal management and Ecotonal NeTworks (ENTs)

Ecological fluxes for any given natural system cannot be usually provided artificially, either due to lack of ecological knowledge, or for technical and economic limits. Therefore, a rational approach to the sustainable protection of natural areas would be to (i) maximise the diversity of the managed systems within the original landscape, and (ii) create and manage a dynamic network of ecotonal connections maintaining fluxes of energy and matter between them (Ecotonal NeTworks, or ENTs). Being inherently more resilient, such managed networks of natural subsystems would provide more sustainable and richer economic and ecological services, allowing for a rational integration of highly interconnected urban subsystems. For instance, several recent strategic plans in Australia and US focused on ecological connectivity of habitats in fragmented landscapes, e.g. through the management of 'biolink zones' (DSE 2008).

In coastal areas, the economic values of each ecosystem can be substantial (e.g. Costanza et al. 1997), especially when considered as long-term investments. On the other hand, the holistic properties of the interconnections between traditionally defined coastal ecosystems (e.g. coral reefs, seagrass beds, mangrove forests, peat swamps, freshwater swamps) have only recently being perceived as intrinsic economic and ecological values (e.g., Yu 2005). Even if such holistic properties could be even more valuable than the isolated ecosystems, these values have not been scientifically quantified, thus being ignored by economists and governments in most tropical countries. Furthermore, conservation or management approaches put a disproportionate emphasis on pollution relative to other types of anthropogenic impact, which directly disrupt internal connectivity, such as habitat loss

and structural/functional impairment of the watershed hydrology (e.g. PEMSEA 2007b). In other cases, socio-economically and politically 'more feasible' conservationist approaches are often demagogically advertised and followed, with considerable waste of resources. This is almost invariably the case of mangrove rehabilitation or restoration activities: extensive reforestation has been routinely and nonsensically conducted in areas under negative sedimentary balance, thus being doomed to fail, while the real anthropogenic factors acting from land, such as watershed hydrological and sedimentological impairment, are fundamentally ignored, due to administrative, legal and socio-economic problems (Hogarth 2007, pers. obs.).

In particular, since coastal zones are progressively developed from land, rationally managed or protected coastal areas are frequently characterized by (i) a spatial arrangement either as a 'belt' along coast of variable width (e.g. Polgar & Bartolino 2010), or isolated patches (e.g. UNDP 2006); and (ii) a deep alteration of the hydrology and sediment dynamics of the whole system, caused by reclamation and land use (e.g. by reclamation bunds, as in the Kuala Selangor Marine Nature Park, Malaysia; pers. obs.). This results in a reduced connectivity between different habitats, with impacts on biodiversity that are similar to the reduction of habitat size (e.g. Nisbet 1968).

Therefore, aiming at the sustainability of managed and protected systems by rehabilitating their homeostasis, it is proposed that (i) single protected areas are not oriented as belts along coast or isolated patches, but as 'transects' along the topographic profile from sea to land, crossing whole sub-basins and watersheds (Fig. 4); and that (ii) hydrological and ecological connections between different types of ecological subsystems within and amongst the protected areas are rehabilitated by a careful water management plan at the watershed level (**Figs. 4-6**).

Ecological transitions across coastal areas including functional hydrological units can be distributed from land to water bodies, from coast to coast in small islands, and along rivers (Fig. 4). In this way, transect-like areas would include different portions of the ecological transition, which will be inherently more diverse, internally connected, biocomplex and resilient.

In tropical Southeast Asia, periodically flooded freshwater swamps and fluvial discharge provide mangrove forests of freshwater input, while peat swamp forests act as water reservoirs for marginal habitats during drier periods (Duke and Wolanski 2001, Hogarth 2007, Yule 2010). Many species, including several ones of commercial importance or particular naturalistic interest (e.g. fishes, crustaceans, monkeys, apes, birds), actively move between these systems, following seasonal, climatic or tidal fluctuations, or during their life histories (Cannicci et al. 2008, Nagelkerken 2009). Therefore, interconnecting such ecological subsystems and managing the whole network at the watershed level, would drastically increase the capability of maintaining homeostasis of its components.

The described multiple-use management and the zoning strategies may be profitably applied to transect-like designs of conserved/managed areas (**Fig. 4**).

In particular, the strategy to promote the local stewardship and management of sub-basins by local communities (PEMSEA 2007b) particularly fits the zoning concept, and the integrated vision of transitional ecosystems.

Of course, the effectiveness of transect-like designs also greatly depends on its geographical scale. For any given available area, a transect-like design would imply much smaller habitat-specific communities and populations than a belt-like design. On the other hand, in this latter case many habitats would entirely disappear, as it is presently the case. Possible solutions could be (i) to scale the transect-like area so as to include minimum viable populations of the hosted species with the largest minimum viable areas (e.g. large mammals or birds); and (ii) to create more transects along coast separated by distances determined by the minimum dispersal ranges of the hosted species, and connected by ecological corridors between the different subsystems (**Fig. 5**: R1-R3; **Fig. 6**: mangrove systems in the foreground). An ecological corridor along the lower forested shore (R1, 100-200 m wide) would also provide an ecological buffer to marine energetic events.

Such design would allow terrestrial, marine and aerial gene flow between each conservational unit, eventually creating a mosaic of conserved, rehabilitated, managed and urbanised zones in the whole catchment area. In this respect, an enhanced research effort of conservation geneticists and molecular ecologists is urgently needed, to inform and support ecosystem-based management with measures of minimum viable areas, minimum viable population sizes, and dispersal capabilities of the species of these communities.
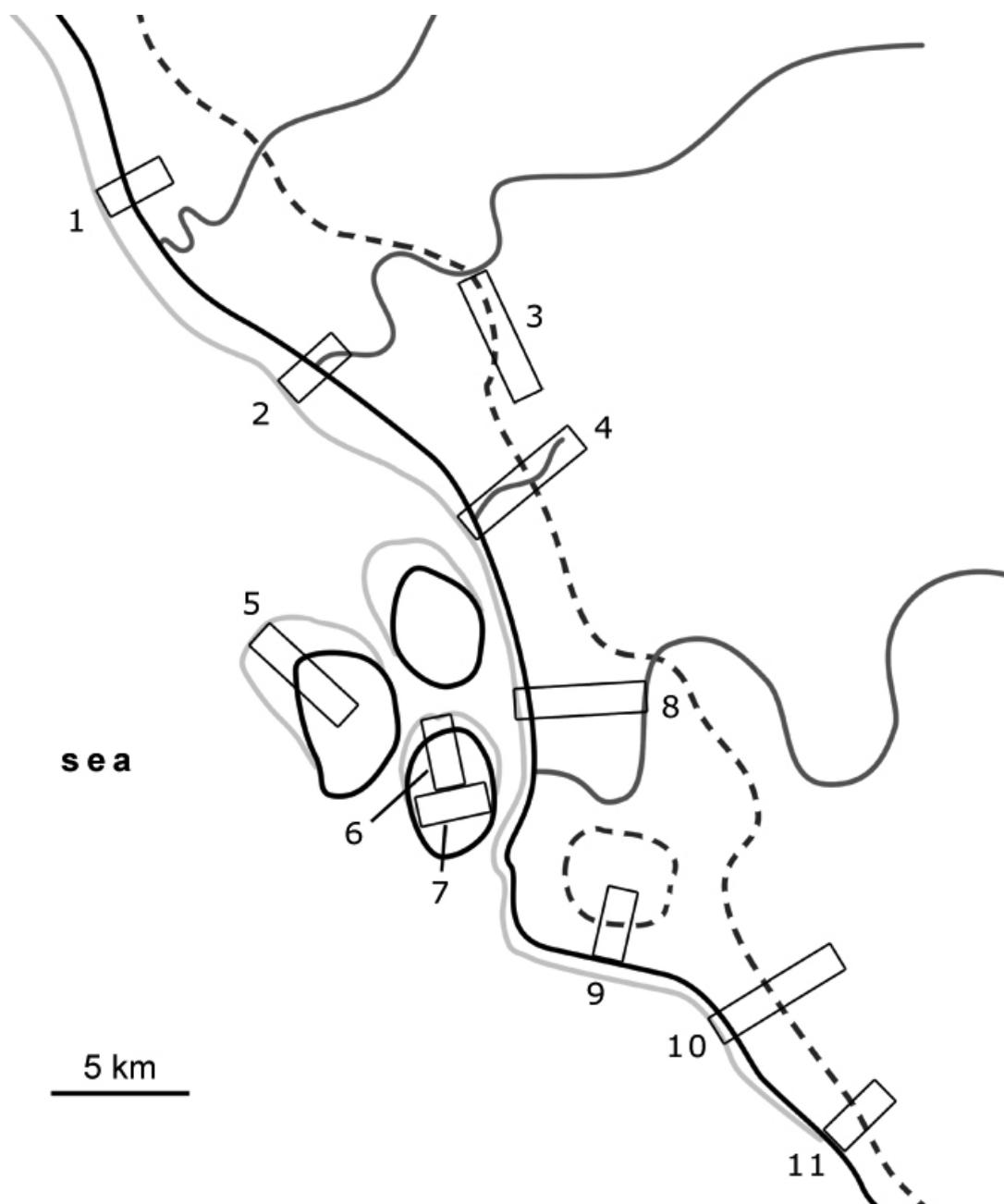
Figure 4. Different examples of transect-like managed coastal areas. The hypothetical coastline is similar to the actual coast of western Peninsular Malaysia (e.g. Coleman et al. 1970); the real distribution of Malayan coastal swamps is now much more fragmented and coastal freshwater swamps almost completely disappeared. *Black line*: coastline; *pale grey line*: outline of mudflats during mean low tide; *dark grey lines*: rivers; *interrupted lines*: contact zone between mangrove forests and freshwater or peat swamps. The geometric shapes of the managed areas are simplifications. Belt transects may include a mudflat and a mangrove forest, with or without the mouth of a river (1, 2, 5, 6); can connect the sea to the banks of a river (8); connect the opposite coasts of a small island (7); include a large portion of a river or a large creek (4); part of the transition from the banks of a river to the flooding plain, including or not the contact zone between different coastal swamps (3); the sea-land transition from mangrove forests to freshwater or peat swamps (9, 11); or wide transitions from mudflats to freshwater swamps and lowland forests (10). Each case would both imply different water management plans, and different ranges of multiple-use conflicts. On the other hand, the ecological connectivity within each protected area would be greatly enhanced.
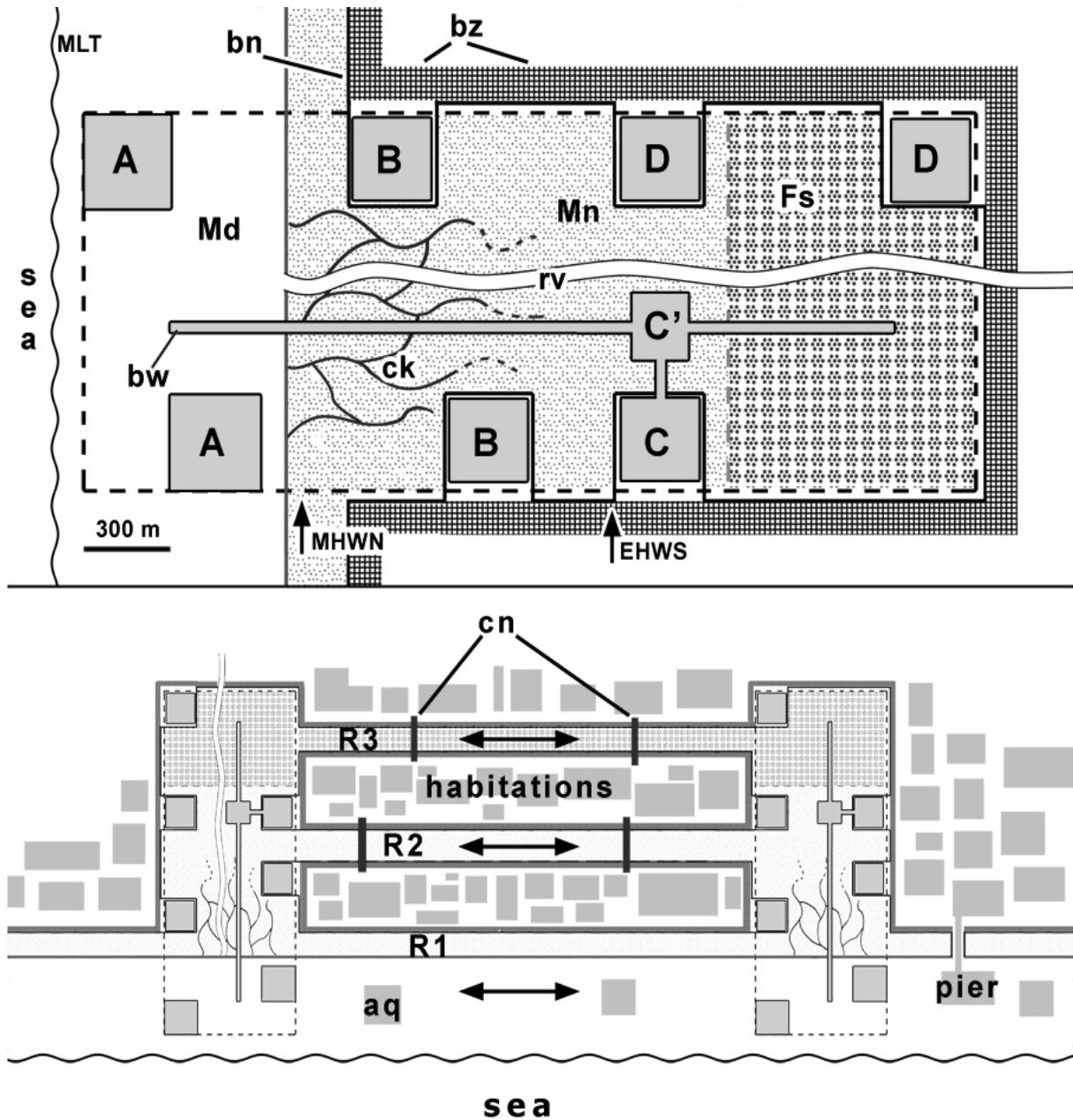
Figure 5.   *Above*: hypothetical example of a transect-like managed coastal area with sustainable multiple uses of the resources. A mudflat (Md), a mangrove forest (Mn), and a freshwater swamp (Fs) are included in an area of 1 km x 3 km. Less than 20% of the total area is managed: the rest is conserved or rehabilitated; the sea is on the left. bn: reclamation bunds/channels to control flooding; bw: boardwalk; bz: buffer zone; ck: creeks' network; MLT: mean low tide; rv: river. A: clam cultivations; B: shrimp farms; C: ecotouristic facility; C': system of boardwalks; D: rotational forestry. The river and creeks' network are part of the water management plan and must be carefully designed to provide both the needed tidal flooding and freshwater supply to the mangroves, and the periodical flooding of the freshwater swamp. *Below*: diagram illustrating the connection between two adjacent transect-like coastal areas. Each zone is connected by a corridor (R1-R3) which crosses reclaimed areas with habitations or other human activities. Corridors allow gene flow (*double arrows*) between the populations hosted in the two conserved/managed areas. To connect reclaimed areas, roads can be built either on bridges or on underground passages (cn), to preserve the ecological continuity along corridors. A stripe of mangrove vegetation of 100-200 m along coast (R1) acts as a barrier to energetic marine events; aq: aquaculture facility. Drawings not to scale.
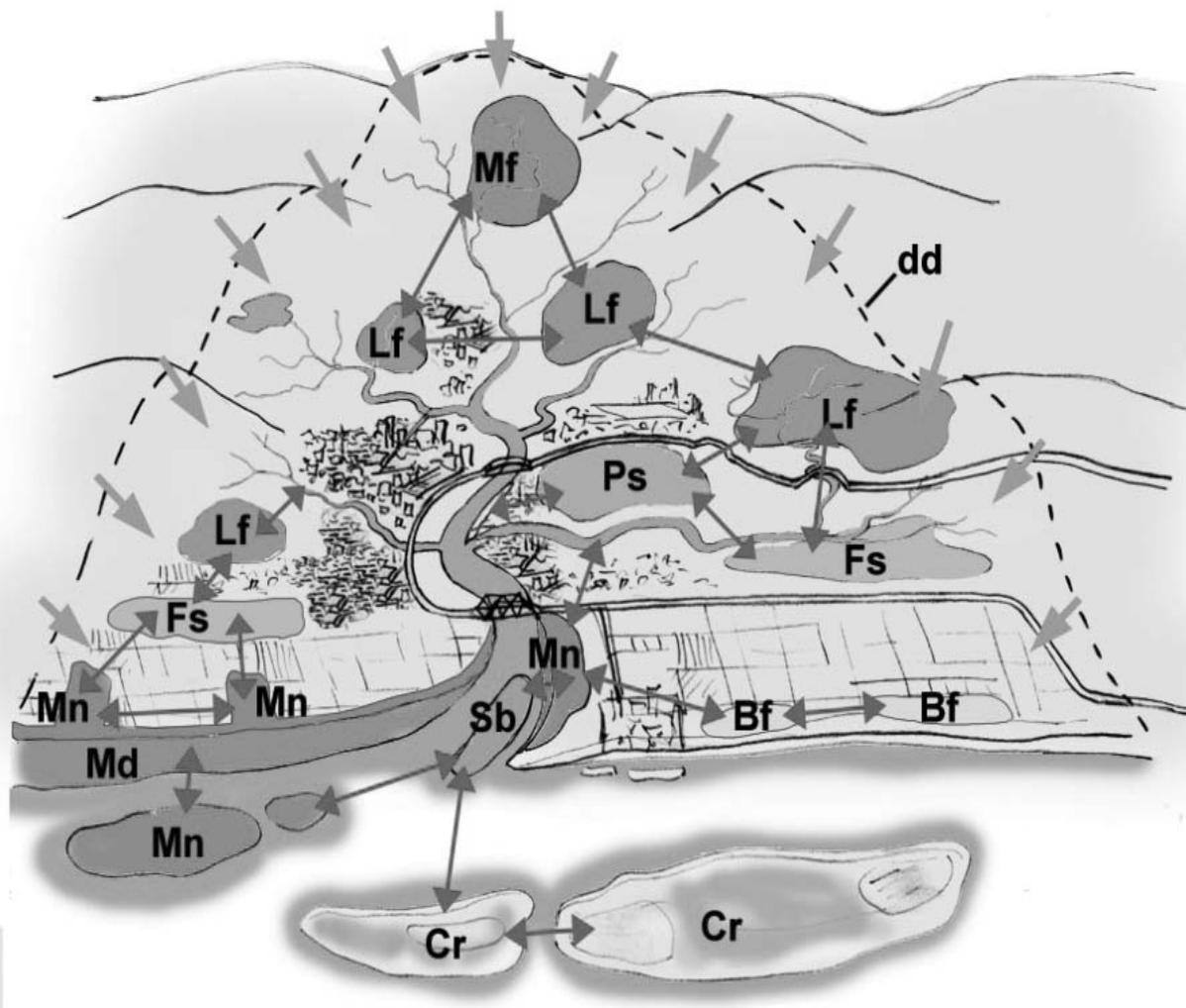
Figure 6. Diagrammatic representation of a tropical watershed. The watershed is an ecological unit, unified by the water flowing (blue single arrows) through the topographic gradient below the drainage divide. Water also closely connects it to the near shore water seascape and its ecosystems (e.g. coral reefs). In this ideal watershed management plan, the different types of natural systems are connected by ecological corridors, stepping stones and/or restored hydrological connections (red double arrows). Managed connections connect subsystems not only along water-to-land transitions, but also across them. In blue = waterways; Bf = beach forest; Cr = coral reef; dd = drainage divide (hatched line); Fs = freshwater swamp; Lf = lowland dipterocarp rainforest; Md = mudflat; Mf = mountain forest; Mn = mangrove forest; Ps = peat swamp; Sb = seagrass bed.

The integrated management of whole watersheds and marine areas issues a harsh challenge to governments, institutions and managers, in the attempt to solve widely debated issues such as the definition and demarcation of landward and seaward boundaries (often completely unrelated to ecological concepts; e.g. PEMSEA 2007a); the integration of multiple-use economic conflicts within and among different sectors; institutional issues and management capacity (lack of human, legal, scientific and financial resources); cross-jurisdictional problems; and the functioning of the administrative framework (UNDP 2006).

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