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Effects of different management regimes on mangrove ecosystem services in Java, Indonesia

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ABSTRACT

Over half of the mangroves in Indonesia have been degraded or converted for aquaculture. We assessed the consequences of management decisions by studying the effects of different management regimes on mangrove ecosystem services in Java, Indonesia. A novel typology of management regimes distinguishes five main categories: *natural*, *low intensity use*, *high intensity use*, *mangroves converted for aquaculture* and *abandoned aquaculture*. Eleven specific management regimes were distinguished, based on legal status, management activities and aquaculture indicators. We assessed and verified matching ecological characteristics per regime. We identified key ecosystem properties underpinning service provision and 'state' and 'performance' indicators for seven ecosystem services: food, raw materials, coastal protection, carbon sequestration, water purification, nursery and nature-based recreation. Service provision was estimated and scored for each regime by relating their ecological characteristics with ecosystem service indicators. *Natural mangroves* scored highest for most services, except for food. High food production in *aquaculture* occurs at the expense of other services. Transitions between management regimes were illustrated to show consequences of management decisions. This study shows the merits of quantifying multifunctionality of management regimes in mangrove systems. Our findings contributed to a common vision among Javanese decision makers to include mangrove ecosystem services in their sustainable coastal management plan.

1. Introduction

Indonesia has the largest extent of mangroves in the world (Spalding et al., 2010). Mangroves occur in the intertidal zone and can include both the trees and their ecosystems (Spalding et al., 2010). Mangroves can endure frequent inundation, high wave energy and varied salinity gradients, which makes them highly adaptable to harsh environments (Walters et al., 2008). Since the 1980s, the extent of Indonesian mangroves has declined from 4.5 to under 3 million hectares (Giesen et al., 2006, Spalding et al., 2010). Mangroves are mainly converted into aquaculture, but timber extraction and the expansion of urban areas and agriculture also contribute (Giesen et al., 2006).

Various scientists have used the concept of ecosystem services to emphasise the various consequences of mangrove decline (e.g. Barbier et al., 2011, Rönnbäck, 1999). Ecosystem services are the contributions to human wellbeing (TEEB, 2010) and mangrove ecosystem services include food, fuel wood, coastal protection and nursery for fish and crustaceans. Ignoring mangrove ecosystem services in policy and management decisions is the major reason

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for continued mangrove conversion and degradation (Barbier et al., 2011). Rather than quantifying ecosystem service provision in non-monetary terms (e.g. biophysical, intrinsic values or human dependence), the monetary value of ecosystem services is often emphasised and communicated (c.f. Schröter et al., 2014). Monetary valuation offers interesting insights, but generally ignores differences in underlying environmental and socio-economic properties, and management (Barbier et al., 2011; Rönnbäck, 1999). Therefore, monetary valuation of ecosystem services could be strengthened by quantifying the interactions between as well as the effects of human activities on ecosystem properties and the services they underpin (Barbier et al., 2011).

Land uses in mangrove systems typically relate to the land–water interface and supporting management activities include harvesting wood, replanting mangrove trees but also fishing and aquaculture management. Land use refers to the purpose of management activities (e.g. fish and timber production, biodiversity conservation) and can be influenced by legislation, socio-economic development etc. (Verburg et al., 2013). Management regimes are the bundle of human activities that serve land-use purposes (Van Oudenhoven et al., 2015). Knowing the effects of management regimes on mangrove ecosystem services allows decision makers to assess consequences of decisions and develop management plans accordingly. Empirical evidence on management outcomes is needed to support decision making because many management assumptions have not been tested or verified (Carpenter et al., 2009).

This study assesses the consequences of management decisions in mangrove systems of Java, Indonesia, by analysing the effects of different management regimes on mangrove ecosystem services. Java was chosen because this island is heavily impacted by management activities for different land uses, and many national government decisions are first implemented here. However, data on management, ecological characteristics and ecosystem services is scarce. Based on literature research, we collected key indicators for seven mangrove services, which were selected in agreement with decision makers. We developed a typology of five main and eleven specific management regimes, which was verified by rapid field assessments in Java. The management regime typology and ecosystem services indicators apply to mangrove systems in the context of Indonesian legislation and Javanese management practices and ecological characteristics resulting thereof. The consequences of each management regime for ecosystem service provision were assessed and compared, and we furthermore illustrate transitions between management regimes.

2. Methods

2.1. Research framework

Many factors influence management activities, but policy and decision making are the most important factors (Fig. 1), for instance through issuing fishery licences, allowing mangrove conversion or demanding protection. Management is considered the key driving force that affects ecosystem properties underpinning ecosystem service provision. Driving forces other than management (e.g. climate, seasonality) are also considered for some services. The typology of management regimes helps to systematically select and study ecosystem properties underpinning, and 'state' and 'performance' indicators of ecosystem service provision (Fig. 1).

2.2. Developing a management regime typology

We aimed to develop a typology that could be applied to mangrove systems in Java and, when modified, the whole of Indonesia. The typology was based on scientific literature and Indonesian legislation, which ensured consistency with the Indonesian policy context and international scientific knowledge. The typology's main categories were inspired by Van Oudenhoven et al. (2015) and furthermore based on classifications of global land-use studies by Verburg et al. (2013), Van Asselen and Verburg (2012) and Alkemade et al. (2009), and other studies (see references in Table 1 and footnote in Table 3). The five main categories reflect increasing land-use intensity and overuse (i.e. abandonment): *natural*, *low intensity use*, *high intensity use*, *converted for aquaculture* and *abandoned aquaculture*.

We then developed eleven specific management regimes based on a combination of policy status (legislation), management activities and aquaculture indicators (Table 1). Matching ecological characteristics per management regime were then established for the Javanese context, based on the literature (Table 4). To further confirm that the management regimes would apply broadly to the Javanese context, we conducted a rapid field assessment between December 2012 and January 2013 in three study sites in Java of one to two weeks per location: Banten, Pemalang and Pangpang Bay, Banyuwangi (see Fig. 2). We first conducted informal, semi-structured interviews with mangrove ecology and aquaculture experts, pond owners, fishermen and other local stakeholders, and district government representatives to verify management

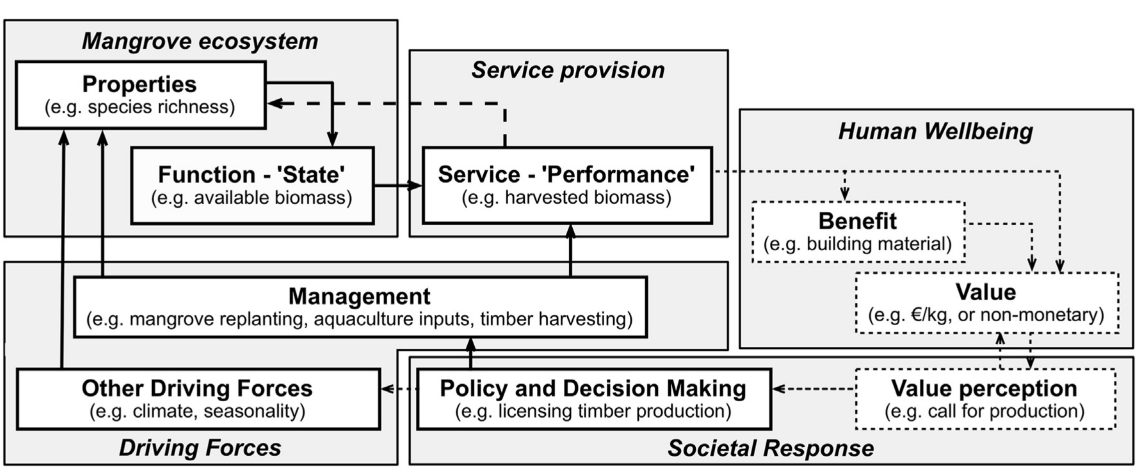

Fig. 1. Research framework, adapted from Van Oudenhoven et al. (2012). Examples between parentheses refer to raw materials provision. Solid arrows indicate direct linkages; dashed arrows indicate potential feedbacks. Boxes and arrows with dotted (out)lines were not considered in our study.

Table 1
Characteristics of management regimes in mangrove systems in Java, based on our literature review. Management activities and biophysical characteristics in italics were ignored for our typology of management regimes.

A) Context of management: Policy status	**Source**
Jurisdiction of an area; Ministries of Forestry, Fishery, Agriculture or district bureau of Spatial planning	Forestry act No. 41/1999, 'Guidelines for mangrove management models' (GMMM) by the Ministry (Min.) of Forestry (2012), Presidential Decree No.73/2012, Sualia et al. (2013)
Ownership status of an area	Peña-Cortés et al. (2013), Sualia et al. (2013)
Targeted ecological and/or economic function	Forestry act No. 41/1999, GMMM by Min. of Forestry (2012), Presidential Decree No.73/2012, Sualia et al. (2013), Walters et al. (2008)
Activities that are allowed or forbidden	Government regulation (Reg.) No. 28/2011, Min. of Forestry Reg. No. 3/2004, Sualia et al. (2013)
B1) Management activities	**Source**
Fishing (with nets, lines, boats)	Gilbert and Janssen (1998), Manson et al. (2005)
Hunting (monkeys, birds)	Sualia et al. (2013), Walters et al. (2008)
NTFP harvesting	Forestry act No. 41/1999, GMMM by Min. of Forestry (2012), Presidential Decree No.73/2012
Timber harvesting	Forestry act No. 41/1999, GMMM by Min. of Forestry (2012), Walters (2004, 2005b), Sualia et al. (2013)
Construction and maintenance of recreation facilities	GMMM by Min. of Forestry (2012), Knight et al. (1997)
Recreational visits by tourists	Gilbert and Janssen (1998)
Replanting of mangrove	Forestry act No. 41/1999, Min. of Forestry Reg. No. 3/2004, Sualia et al. (2013)
Domestic waste or aquaculture effluent disposal	Knight et al. (1997), Primavera et al. (2007)
B2) Aquaculture management indicators	**Source**
Natural or artificial stocking	Gilbert and Janssen (1998)
Use of artificial fertilizer, pesticide and/or antibiotics	Gautier (2002), Rönnbäck (2001)
Stocking density	Gautier (2002), Rönnbäck (2001),
Size of aquaculture ponds	Gautier (2002), Primavera et al. (2007), Rönnbäck (2001)
Water exchange technique	Kusmana et al. (2008), Primavera et al. (2007)
Natural or artificial feed	Gilbert and Janssen (1998), Rönnbäck (2001)
Aeration of aquaculture ponds	Kusmana et al. (2008)
C) Ecological and biophysical characteristics	**Source**
Number of true mangrove species (richness)	Primavera (1998)
Average diameter at breast height (d.b.h)	Komiyama et al. (1996)
Maximum height of mangrove trees	Bengen (2003), Komiyama et al. (2008)
Maximum age of mangrove trees	Clough et al. (1997)
Maximum perimeter of mangrove trees	Manson et al. (2005), Mumby et al. (2004),
Maximum root length of mangrove trees	Farnsworth and Ellison (1996)
Undergrowth	Matthijs et al. (1999)
Nr. of seedlings and saplings	Primavera (1998)
Temperature of substrate, water	Middelburg et al. (1996)
Soil substrate	Middelburg et al. (1996), Schrijvers et al. (1995)

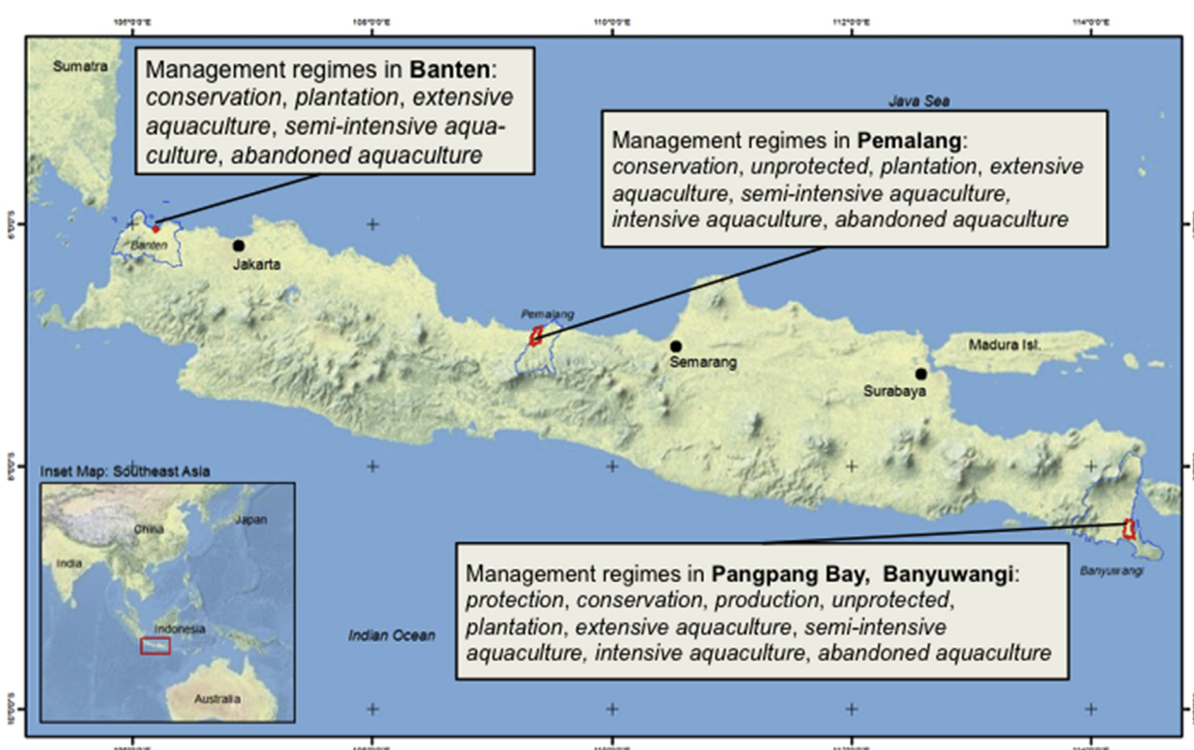

Fig. 2. Map showing the three study sites in Java where rapid field assessments were conducted to verify management regimes. We list the management regimes that could be found per study site.

Table 2
Drivers, ecosystem properties and state and performance indicators of mangrove ecosystem services. Terms in bold italics were considered in our analysis. References are provided in footnotes.

Ecosystem service	Drivers of service provision (including management)	Ecosystem properties underpinning ecosystem service provision	State indicator (unit)	Performance indicator (unit)
Food (fish and shrimp)	***Nursery service***[1,2,3,4]; coastal fishing intensity[2,4]; ***aquaculture inputs***[2]	***Nutrient availability***[1,2,3]; water quality[2]; predation[3]; trophic subsidy[2,3]	***Available stock*** (kg yr^{-1}; kg ha^{-1} yr^{-1})[5,6]	***Actual harvest*** (kg yr^{-1}; kg ha^{-1} yr^{-1})[6,7,8]
Raw materials (tree biomass)	Climate and seasonality[10,14]; ***protection status area***[13,14]; ***harvesting methods***[14]; desired end-use[10,14]; proximity user to forest[13,14]	***Species richness***[9,10]; tree density[9,11], ***diameter***[10,11], ***height***[9,10,11], ***age***[9,10] and ***productivity***[9,10,11]; fraction dead wood, litter[10]; soil substrate type[10,11]; forest size[9,10,11]; inundation, flooding pattern[10,11,12]	***Available tree biomass for human use*** (ton yr^{-1}; ton ha^{-1} yr^{-1})[9,10]	***Actual tree biomass harvested for human use*** (ton yr^{-1};ton ha^{-1} yr^{-1})[9,15]
Carbon storage and sequestration	***Long-term protection***[10,12,21]; ***restoration***[10,12,20]; climate[12,16]; temperature[12,16]; hydrological management[12,16,20]; distance from seaward edge[20]	Soil and sediment type[12,16,17]; soil depth[17,18,19,20]; organic matter content[12,19,20]; soil inundation[12,20]; tide[12,16,20]; ***tree diameter***[10,11,16,18], ***age*** and ***size***[6,17,20]; stem density[16,17,20]; riverine inputs[12,17]; ***species richness***[17,18,20]; nutrient availability[12,17,18,20]	***Carbon storage*** (ton ha^{-1})[10,16,20]	Difference between carbon stocks of intact and impacted mangroves (ton ha^{-1} yr^{-1})[12,20]
Coastal protection (wave attenuation, storm surge protection)	Wave period and height[25,28] Topography[24,26]	Extent or width of forest[22,23,24]; ***species richness***[22,24]; ***structural diversity***[22,23,24]; ***tree age***[22,24]; water depth[26,28]	***Projected area of mangroves*** (m^2)[22,23]; width of mangrove greenbelt (m)[22,23]	Wave height reduction rate (m^{-1})[27,28]; wave energy dissipation[27,28] Storm surge reduction rate (m^{-1})[29]
Water purification (N & P removal)	***Biomass harvest***[30,31]; ***mitigated disturbance of sediment***[30,31,33]; ***nutrient output of aquaculture system***[30,31,32]	***N & P requirements of trees***[30,31,32]; litterfall[30]; biomass accumulation[30,31]; ***physically stable sediment***[30,33]; mangrove area[30,31,32]; plant density, structure[31,32]; ***photosynthesis rate***[31,33]; water salinity[31,33], flow speed[30,31]; clay mineralogy, iron content[30,33]; redox status[33]	***Potential N and P removal*** (mg ha^{-1} yr^{-1})[30,31]	***Actual N and P removal*** (kg ha^{-1} yr^{-1})[30,31,34]
Nursery service	Mitigation of pollution, overfishing and other pressures[3,5,35]	***Nutrient trapping***[3,5,25,35]; ***tidal mixing***[3,35,36]; freshwater inflow[3,25,36]; turbidity[3,36]; ***roots***[3,5,25]; spatial and trophic niches[3,35,36]; hydrodynamic cycles retaining larvae and juveniles[3,5,35,36]; ***intact hydrological cycles***[3,35]	***Relative contribution to fish and shrimp stock***[5]; fraction of mangrove-dependent juvenile species that mature into adults[3]	***Fish and shrimp harvest per area of mangrove***[7,35]; relative contribution to harvest[5,35,36]
Nature-based recreation	***Supporting infrastructure***[37,38,39]; ***recreation facilities***[38,39,40]; noise level[38,39]; crowdedness[38,39,42]; travel distance[39,40]; skyline disturbance[38,39,41]	***Flora and fauna***, land cover, ***land use***, and/or ***cultural element with stated preference***[37,38]; condition of ecosystem[37,38,39]	Potential number of visitors (# yr^{-1};# ha^{-1} yr^{-1})[37,38,42]	Actual number of visitors[38,40,42]; boat hires[40,42]; booked trips[38,40,42]

References: 1 Mumby et al. (2004); 2 Rönnbäck (1999); 3 Sheridan and Hays (2003); 4 Naylor et al. (2000); 5 Manson et al. (2005); 6 Rönnbäck et al. (2003); 7 Kathiresan and Rajendran (2002); 8 Aburto-Oropeza et al. (2008); 9 Bosire et al. (2008); 10 Ong (1993); 11 Sukardjo and Yamada (1992); 12 Mcleod et al. (2011); 13 Ewel et al. (1998); 14 Walters (2005a); 15 Walters (2005b); 16 Alongi (2012); 17 Bouillon et al. (2008), 18 Donato et al. (2011); 19 Kauffman et al. (2011); 20 Kauffman et al. (2014); 21 Clough et al. (1997); 22 Massel et al. (1999); 23 Quartel et al. (2007); 24 Vo-Luong and Massel (2006); 25 Walters et al. (2008); 26 Zhang et al. (2012); 27 Mazda et al. (2006); 28 McIvor et al. (2012a); 29 McIvor et al. (2012b); 30 Gautier (2002); 31 Li et al. (2008); 32 Primavera et al. (2007); 33 Robertson and Phillips (1995); 34 Jackson et al. (2003); 35 Baran (1999); 36 Pauly and Ingles (1999); 37 Puustinen et al. (2009); 38 Van Oudenhoven et al. (2012); 39 Boon et al. (2002); 40 Satyanarayana et al. (2012); 41 Rönnbäck et al. (2007); 42 Knight et al. (1997).

regimes. Sufficient interviews were conducted per management regime and study site to verify management activities and aquaculture indicators per regime. The number of interviews ranged between three for *natural mangroves* to at least ten for *mangroves converted for aquaculture*. Most experts and local stakeholders had knowledge about multiple management regimes. Interviews with local stakeholders were conducted in Indonesian, or Javanese when possible, to avoid misinterpretation. Permission for the field assessment was obtained from the local government and permission for each interview was obtained from the local village elder.

We also collected information on mangrove age, height, diameter, perimeter and number of tree species in the mangroves and, where applicable, aquaculture inputs and fish and shrimp harvests. Due to time and budget constraints, insufficient observations were made to map the management regimes or quantify ecosystem services per location. Nine management regimes could be observed at the three study sites; only the *eco-certified aquaculture* and 'ideal' *silvo-fishery* regimes were missing in the study area (see Fig. 2).

2.3. Indicator selection for mangrove ecosystem services

Seven mangrove ecosystem services were selected, based on their relevance for Indonesian policy and stakeholders in Java: food (i.e. fish and shrimp), raw materials, coastal protection, carbon storage and sequestration, water purification, nursery for fish and shrimp, and nature-based recreation. We selected key ecosystem properties, and 'state' and 'performance' indicators for each service, in line with Van Oudenhoven et al. (2012). Ecosystem properties are ecological and biophysical conditions, processes and structures that underpin the ecosystem's capacity to provide ecosystem services

(Van Oudenhoven et al., 2012). Indicators for the 'state' and 'performance' (see Fig. 1), respectively, indicate the ecosystem function or capacity to provide services, and the actual service provision (De Groot et al., 2010, Van Oudenhoven et al., 2012). We also included other drivers and non-ecological factors that determine service provision.

To retrieve the information, we first consulted frequently cited review papers on mangrove ecosystem services, searching 'ecosystem services' AND 'mangrove' in Web of Science™. These papers included Alongi (2012), Barbier et al. (2011), Bosire et al. (2008), Cochard et al. (2008), Walters et al. (2008), Sheridan and Hays (2003), and Ewel et al. (1998). Further information was then obtained from their references and citing papers. We collected recurring information (i.e. confirmed by multiple sources) rather than conducting an exhaustive review. All used references are provided in footnotes of Table 2.

2.4. Analysing ecosystem service provision per management regime

We related information on management activities, aquaculture management indicators and ecological characteristics (Table 4) with underpinning ecosystem properties and state and performance indicators for ecosystem service provision (Table 2). Although few studies explicitly mentioned 'management regimes', we used mentioned ecological and management characteristics from study-site descriptions for assigning the studies to a management regime. We always considered both ecological characteristics and management indicators. Quantitative results were preferred, but these were rarely available for all regimes. Moreover, qualitative information proved more reliable and consistent for especially regulating services. When multiple sources provided quantitative information, the full range of possible outcomes was presented. Some quantitative results for *aquaculture* management regimes were interpolated based on data for other adjacent regimes (e.g. water purification in *semi-intensive* and *extensive aquaculture* were based on combined data on *intensive* and *semi-intensive aquaculture*, respectively).

To compare service provision per management regime, quantitative and qualitative information on ecosystem services was integrated using a scoring system ranging from −3 to +3 and including 0. All ecosystem service scores per regime are provided in Table 5 and illustrated in Fig. 4. Scores of 0,1,2 and 3 related to, respectively, no, low, medium and the highest possible provision for each ecosystem service. Negative scores were assigned in similar fashion, but indicated disservices resulting from a certain management regime, such as CO_2 emission instead of sequestration, water pollution instead of purification and increased flood risk instead of coastal protection. We opted for this simple scoring system, because large scoring ranges would only have decreased the precision and validity of the outcomes. Moreover, the scores enable comparing service provision between regimes within the same policy and management context. The robustness of the results was determined based on availability of multiple sources and multiple indicators, and applicability to the Javanese management and ecological context. Results that were interpolated, based on few indicators, weakly linked to management regimes, and/or of limited applicability to the Javanese context were considered uncertain.

3. Indicators for mangrove ecosystem service provision

Table 2 provides key ecosystem properties and 'state' and 'performance' indicators for seven mangrove ecosystem services. The indicators are explained below and further references are provided in footnotes of Table 2.

3.1. Fish and shrimp provision

We limit our study to fish and shrimp but summarise other food uses per mangrove species in Appendix A. The available stock is an often-used state indicator for fish and shrimp provision and the actual harvest a performance indicator. Both indicators are often related to the area of mangrove or aquaculture pond, which are crucially different systems in terms of ecological properties and management. Natural provision depends on ecological and biophysical characteristics (Table 2) and the nursery service of mangroves and adjacent ecosystems (see Sheridan and Hays (2003) and Section 3.6). Artificial provision in aquaculture systems depends mostly on management inputs (Section 4.4) and involves keeping the stock in an enclosed system and providing it with nutritional and disease preventive requirements (Naylor et al., 2000). Aquaculture also depends on ecosystem services provided by surrounding ecosystems, such as nursery service, water purification and coastal protection (Naylor et al., 2000).

3.2. Raw materials

Raw materials can be harvested from leaves, bark, wood and dead wood (Walters, 2005b). We consider available aboveground biomass for human use a state indicator and the actual (sustainable) harvest indicates the performance. Biomass harvest is considered sustainable if remaining below the forests' net productivity (Bosire et al., 2008, Ong, 1993). Diameter, growing form and stem length ultimately determine raw materials' use, such as fuel wood, fodder and construction material (Walters, 2005b). Because such properties differ per species, mangrove species richness and tree age are suitable proxies for raw material provision (Walters, 2005b). Appendix A relates specific raw materials use per mangrove species.

3.3. Carbon storage and sequestration

Mangroves are productive systems and represent important sinks of carbon (Walters et al., 2008). Carbon storage and sequestration involve different time scales and processes. We consider carbon storage a state indicator for carbon sequestration. Actual sequestration by mangroves is rarely measured, but can be estimated by calculating the difference between carbon storage of intact and impacted mangrove forests (Kauffman et al., 2014, Mcleod et al., 2011). However, the carbon sequestration required for building up carbon stocks, especially in mangrove soils takes decennia, if not millennia (Mcleod et al., 2011).

Carbon is stored as living biomass both aboveground and belowground, as non-living biomass and as organic matter in sediments (Alongi, 2012; Mcleod et al., 2011). Aboveground carbon storage is determined by mangrove age and corresponding factors (Table 2). Soil and root carbon pools also increase with increasing tree age (Alongi, 2012, Donato et al., 2011). Belowground carbon has rarely been measured but is estimated to account for 49–98% of the total carbon stock in mangroves (Donato et al., 2011, Kauffman et al., 2014). While living biomass eventually reaches a dynamic equilibrium, waterlogged mangrove soils continuously accumulate carbon (Alongi, 2012, Mcleod et al., 2011). Moreover, carbon accumulation in mangrove soils depends on climate, soil, sediment type and riverine inputs (Kauffman et al., 2014, Mcleod et al., 2011). Actual carbon sequestration depends on restoration and hydrological management, and long-term protection of vegetation and soil is required to optimise and maintain long-term soil carbon accumulation (Alongi, 2012). Vegetation clearance and drainage will expose mangrove soils and cause oxidation resulting in immediate emission of carbon that may have been sequestered over a very long time (Mcleod et al., 2011, Ong, 1993).

3.4. Coastal protection

Mangroves contribute to coastal protection by reducing the height and impact of waves and storm surges (Mazda et al., 2006, McIvor et al., 2012a). We did not consider soil surface elevation in response to sea level rise, because it involves poorly understood and complex processes (Alongi, 2008).

Wind and swell waves result from tides, wind and storms (Massel et al., 1999). Mangroves act as an obstacle for the oscillatory water flow in waves thus dissipating wave energy and reducing wave height (Mazda et al., 2006). Wave height reduction rate (performance) is indicated as the initial wave reduction over a horizontal distance travelled (m^{-1}), which depends mostly on structural diversity (Massel et al., 1999, Quartel et al., 2007). Forest width and projected area are commonly used to determine potential wave attenuation (McIvor et al., 2012a).

Storm surges are movements of sea water onto land caused by strong winds (McIvor et al., 2012b). Storm surge reduction rates (performance) are harder to establish than for wave attenuation and available information is limited to US-based studies (McIvor et al., 2012b). Factors influencing storm surge protection are similar to those influencing wave attenuation, but their predictive value is lower; contrary to wave attenuation, relationships between underpinning factors and storm surge reduction rates are not linear due to topographical influences, such as by slope and coastal profile (Zhang et al., 2012).

3.5. Water purification

Water purification by mangroves involves the uptake of nitrogen (N) and phosphorus (P) from aquaculture discharge water. Conversely, water pollution can be seen as a ‘dis-service’ of aquaculture (Jackson et al., 2003). Actual nutrient removal indicates the performance and potential removal the state (Table 2). N and P concentrations in discharge water are mostly measured per ha of pond, whereas uptake is mostly measured per ha of mangrove. Mangroves reduce nutrient concentrations in water through biomass uptake and adsorption in stabilized sediments (Li et al., 2008, Robertson and Phillips, 1995). Nutrient removal by mangroves is measured in relation to their N and P requirements, provided that sufficient mangrove area is present and that accumulated biomass is harvested, retained or nutrients are recycled within sediments. N and reactive P can furthermore be immobilised in sediments, which mostly depends on clay mineralogy, iron content and undisturbed sediments (Li et al., 2008, Robertson and Phillips, 1995).

3.6. Nursery service

Mangroves provide nursery ground or living habitat to fish and crustaceans, thus supporting fisheries and some aquaculture systems (Rönnbäck, 1999; Walters et al., 2008). Nursery ground involves shelter, food and refuge, and spawning opportunities (Walters et al., 2008). The fraction of mangrove-dependent juveniles that mature into adults is a common state indicator, but has rarely been quantified or assessed (Sheridan and Hays, 2003). Other proxies for nursery include the stock or harvest per mangrove area and the relative contribution of mangroves to a given harvest (Table 2). Models have related mangrove area with fish and shrimp catches (e.g. Pauly and Ingles, 1999), but any local estimation requires calibrations based on long-term measurements of harvests and mangrove extent. Sheridan and Hays (2003) reviewed that most studies fail to empirically relate the number of juveniles that are recruited in mangrove areas with the extent to which they mature into adults. Important underlying ecosystem properties for this recruitment include the presence of roots and turbid, nutrient-rich water (Table 2). Crucially, mangroves form integrated ecosystems with sea grass beds, un-vegetated shallows and coral reefs (Rönnbäck et al., 1999).

3.7. Nature-based recreation

Nature-based recreation in or around mangroves include diving, bird watching, hiking and fishing. Tourism involves tourists staying over night, whereas recreation describes the activities (Puustinen et al., 2009). The potential number of recreants is a state indicator and actual visitor numbers indicate the performance. An area's suitability for recreation determines recreation and suitability can therefore be used as a proxy for the state indicator (Van Oudenhoven et al., 2012). This suitability depends on the presence of appreciated flora and fauna or culturally important features, which can include rare plants and animals, unspoilt views and traditional land uses (Puustinen et al., 2009). Most recreation requires additional facilities and organisation as well as infrastructure such as roads, parking lots and walking bridges (Table 2). Recreants might be discouraged by lacking facilities, crowdedness, travel distance, damaged or polluted ecosystems etc. (Boon et al., 2002, Van Oudenhoven et al., 2012). We note that recreants' preferences are personal and location-specific, and have rarely been quantified and standardised for mangroves and most other ecosystems.

4. Management regimes in mangrove systems in Java, Indonesia

Our typology distinguishes five main categories of management regimes, based on land-use purpose: *natural* (purpose: preserving biodiversity and ecological and biophysical functions), *low intensity use* (natural resources production), *high intensity use* (mangrove rehabilitation and sustainable food/raw materials production), *converted to aquaculture* (fish and shrimp cultivation) and *abandoned aquaculture* (no purpose). The five main categories are divided into eleven specific management regimes (Table 3). Table 4 summarises management activities, aquaculture indicators and matching ecological characteristics per management regime. The management regimes are written in italics to emphasize that they are part of this study's typology.

4.1. Natural mangroves

Natural mangroves have recognised ecological and biophysical functions that should be formally preserved (Forestry act No. 41/1999). *Natural mangroves* are divided into *protection* and *conservation* management regimes.

Protection mangroves are locally governed for protecting biodiversity and ecological and physical functions, such as nursery, genetic resources and coastal protection. Local people are permitted to fish and hunt, and gather NTFP (non-timber forest products) at low intensity, i.e. without damaging vegetation. Permits are issued for activities related to science, education and research and development. Recreational visits are allowed, but no infrastructure is in place to support recreation.

Conservation mangroves have recognised ecological, economic and biological characteristics and fall under Ministry of Forestry jurisdiction. Their main purpose is preserving biodiversity, natural resources and local culture. According to government regulation No. 28/2011, *conservation mangroves* include reserves, hunting

Table 3
Typology of management regimes in mangrove systems in Java. The main categories are indicated in bold letters.

Management regime[a]	Short description
Natural mangroves	
Protection of ecological and physical functions	Management aims to preserve ecological and biophysical functions and biodiversity. Management activities include hunting on unprotected animals, low intensity NTFP harvesting, fishing and facilitating research.
Conservation of biodiversity and local culture	Management aims to conserve biodiversity and ecological functions, natural resources and local culture. Management activities include facilitating recreation and tourism, hunting unprotected animals, low intensity NTFP harvesting and fishing.
Low intensity use mangroves	
Production of forest products	Management aims at utilizing economic function, which is mainly NTFP and timber production. Management activities include timber harvesting, high intensity NTFP harvesting, replanting mangroves, enabling recreation and fishing.
Unprotected	There is no formal protection in place, due to remoteness or abandonment. Management activities can include timber harvesting, low intensity NTFP harvesting and fishing.
High intensity use mangroves	
Plantation	Management aims at mangrove rehabilitation, slowing down deforestation rate and restore ecological and economic functions, thereby increasing prosperity. Management activities include high intensity NTFP harvesting, recreation, fishing and planting mangroves.
Silvo-fishery	Management combines aquaculture and mangrove replanting and aims to rehabilitate mangroves to reduce deforestation rates, restore ecological and economic functions, thereby increasing people's prosperity. Management activities include high intensity NTFP harvesting, recreation, cultivating shrimp, crab and fish, maintaining dykes and replanting mangroves.
Mangroves converted for aquaculture	
Eco-certified aquaculture	Aquaculture that follows guidelines related to animal health, food safety and quality, environmental integrity and social responsibility. Mangrove rehabilitation and greenbelt protection is required. Management activities include use of artificial stock, high seed density and some fertilizer.
Extensive aquaculture	'Traditional' aquaculture in large ponds, with use of mixed stock, low seed density, limited fertilizer and pesticide, and natural feed. Water exchange occurs through natural tides.
Semi-intensive aquaculture	Aquaculture with use of artificial stock, low to medium seed density, fertilizer, pesticides and mixed feed. Water exchange occurs through water pumps and pedal wheels.
Intensive aquaculture	Aquaculture in small ponds with use of artificial stock, high seed density, fertilizer, antibiotics, pesticide, and formulated feed. Water exchange through water pumps and pedal wheels.
Abandoned aquaculture	
Abandoned aquaculture	Management activities have been abandoned, due to depletion. No regulations apply.

[a] Main categories are based on Verburg et al. (2013), Van Asselen and Verburg (2012), Alkemade et al. (2009), Macintosh et al. (2002), Stevenson (1997). Specific management regimes are based on Gilbert and Janssen (1998), Sofiawan (2000), Rönnbäck (2001), Bengen (2003), Primavera et al. (2007), Kusmana et al. (2008), Walters (2005b), Barbier et al. (2011) and Indonesian policy documents: Forestry Act No. 41/1999, Government Regulation No. 10/2010 and No. 28/2011, Ministry of Forestry Regulation No. 3/2004 and 'Guidelines for development of mangrove management models' by the Ministry of Forestry (2012).

parks, national parks and recreation parks. Recreation facilities (e.g. walking tracks, signs) are maintained to promote recreation. Local communities are permitted to fish and hunt, and gather NTFP at low intensity.

4.2. Low intensity use mangroves

Low intensity use mangroves are natural or replanted forests that are used for NTFP and timber harvesting (Forestry act No. 41/1999). They can be managed through private ownership, by local or regional governments, or, due to lacking protection, be freely used. We distinguish between *production* and *unprotected* regimes.

Production mangroves have a formally recognised economic function in timber and NTFP production. High intensity timber and NTFP harvesting occurs, which involves intensive management. Replanting trees is compulsory if the forest's ecological integrity is affected by management activities. Local people are permitted to hunt and fish. Recreation occurs at or around *production mangroves*, but no supporting infrastructure exists.

Unprotected mangroves fall under no formal jurisdiction and lack specific land-use purpose. This diverse regime includes formerly *abandoned aquaculture* and restored or left-alone mangroves. *Unprotected mangroves* also include mangroves that are gradually restoring because of unintentional protection, for instance due to social unrest or limited accessibility. Low intensity harvesting and limited timber cutting can occur, due to the combination of weakly enforced regulation and limited accessibility.

4.3. High intensity use mangroves

High intensity use mangroves are formally regarded as rehabilitation sites (Presidential decree No. 73/2012). Their main purpose is mangrove restoration combined with sustainable shrimp or raw materials provision. We distinguish between *plantation* and *silvo-fishery* regimes.

Plantation of mangroves generally involves 'silviculture', i.e. the controlled sustainable growth of mangroves to meet landowners' needs (Walters et al., 2008). Ministry of Forestry regulations apply. Mangroves can be either planted or regrown due to controlled regeneration (Bosire et al., 2008) and function to provide raw materials, support fisheries, aquaculture and tourism, or to enhance coastal protection (Walters et al., 2008). Fishing and high intensity NTFP harvesting take place in *plantations*. Tourists can visit for fishing, birding, hiking etc. No timber harvesting occurs, and mangroves are replanted when needed.

The goal of *silvo-fishery*, according to Ministry of Forestry Regulation No. 3/2004, is to rehabilitate ecological and economic functions of mangroves, i.e. to provide services such as coastal protection and nursery without impairing shrimp aquaculture. Regulations from the ministries of Forestry, Regional Spatial Planning and Fishery apply. Supposed benefits and services of *silvo-fishery* include stronger pond embankments, fodder provision, nursery service, salt water intrusion prevention and coastal protection (Bengen, 2003, Sofiawan, 2000, Sualia et al., 2013). The *silvo-fishery* regime considered here provides all formally targeted functions (Bengen, 2003). This 'ideal' option is illustrated in Fig. 3. We note that 'ideal' *silvo-fishery* is virtually absent in Java, due to limited knowledge on optimal management and the relatively small size of ponds that are rehabilitated. In Appendix B we summarise this option and eight other *silvo-fishery* variations based on reviewing the Indonesian scientific literature. Most other variations will provide few ecosystem services, due to how and where mangroves are planted, differing water in- and outlets etc.

Table 4
Management activities, aquaculture indicators and ecological characteristics of management regimes in mangrove systems in Java. Ecological characteristics are based on the literature (see footnotes) and field observation.

Management regime	Management activities					Aquaculture management indicators					Ecological characteristics of mangrove trees							
	Recreational visits (Y/N)	Fish-ing (Y/N)	Timber harvesting (Y/N)	NTFP harvest intensity	Man-grove replanting (Y/N)	Avg. pond size (ha)	Origin stock	Stock density (m^{-2})	Origin additional feed	Use of fertilizer, pesticide	Avg. # species	Avg. d.b.h (cm)	Max. Height (m)	Max. age (yr)	Max. perimeter (cm)	Max. root length (m)	Undergrowth	Seedlings, saplings #
Protection	Y	Y	N	Low	N	–	–	–	–	–	≥4	17–22	≥30	20–30	50–70	>1.5	Clear	Low
Conservation	Y	Y	N	Low	N	–	–	–	–	–	3–4	12–16	≥30	12–19	30–50	>1.5	Few shrubs	Medium
Production	Y	Y	Y	High	Y	–	–	–	–	–	3–4	<13	<30	10–16	<40	<1.5	Shrubs	Medium
Unprotected	N	Y	Y	Low	N	–	–	–	–	–	3–4	<13	<30	10–16	<40	<1.5	Shrubs	Medium
Plantation	Y	Y	N	High	Y	–	–	–	–	–	≤3	<11	<20	7–10	<35	<1	Shrubs	High
Silvo-fishery	Y	N	N	High	Y	>1.5	Nat	1–3	Nat.	P	≤3	<11	<20	7–10	<35	<1	Shrubs	High
Eco-certified aquaculture	Y	–	N	–	Y	0.1–1	Nat, A	10–50	Nat.	F/P	≤2	<7	10–20	<10	<20	–	No	High
Extensive aquaculture	N	–	N	Low	N	1–10	Nat, A	1–3	Nat.	F	≤2	<3	10–20	4–6	<10	–	No	High
Semi-intensive aquaculture	N	–	N	–	N	1–2	Nat, A	3–10	Nat., A	F/P	≤2	<3	10–15	<4	<10	–	No	Medium
Intensive aquaculture	N	–	N	–	N	0.1–1	A	10–50	A	F/P	1	<2	10–15	2–4	<5	–	No	Low
Abandoned aquaculture	N	N	N	–	N	–	–	–	–	–	≤2	<1	<1	1–2	3	–	Stumps, shrubs	Low

Note: Y/N = Yes/No; – = not applicable; Nat = Natural; A = Artificial; F = Fertilizer; P = Pesticide; Stock density refers to shrimp; d.b.h. = diameter at breast height. Furthermore, the combination of roots, branches, undergrowth can be described as 'structural diversity'.
Sources for indicators of management: Bengen (2003), Gilbert and Janssen (1998), Kusmana et al. (2008), Macintosh et al. (2002), Primavera et al. (2007), Rönnbäck (2001), Sofiawan (2000), Stevenson (1997), Sualia et al. (2013), Walters (2005b), and Indonesian policy documents: Forestry Act No. 41/1999, Government Regulation No. 10/2010 and No. 28/2011, Ministry of Forestry Regulation No. 3/2004 and 'Guidelines for development of mangrove management models' by the Ministry of Forestry (2012). Sources ecological characteristics: Bengen (2003), Kusmana et al. (2008), Middelburg et al. (1996) and Schrijvers et al. (1995).

'Ideal' *silvo-fisheries* have a centrally located mangrove patch surrounded by a large ditch (Fig. 3). Water and nutrients are circulated through natural tidal movement, further stimulated by two water inlets. An outlet directs effluent through the mangroves, which removes excess nutrients. Only natural shrimp stock is added and no additional feed or fertilizer is used. We noted limited pesticide use. *Silvo-fishery* ponds are generally around 1.5 ha, but pond size can vary as formerly used *aquaculture* ponds are usually rehabilitated. Recreational visits are common in *silvo-fishery* sites and involve fishing, boardwalks and education. Furthermore, NTFP are harvested at high intensity. The assumed ideal pond-mangrove ratio is 60:40 (Bengen, 2003; Bosma et al., 2014).

4.4. Mangroves converted for aquaculture

Aquaculture ponds are owned or rented by the private sector, which follows regulations by the ministries of Environment, Public Works, Agriculture and Fishery. Regulations are often combined or 'creatively' interpreted (Sualia et al., 2010) and can be overruled by ordering mangrove conversion or aquaculture expansion. We distinguish between *eco-certified, extensive*, *semi-intensive* and *intensive aquaculture*, mainly based on stocking density and the type of feed and fertilizer. We did not consider the effects of conversion, as all other management regimes have also been described as 'steady states' characterised by current management alone. The characteristics provided below apply to both shrimp and fish aquaculture, unless stated otherwise.

Although *eco-certified aquaculture* is currently absent in Java, requirements for certification were recently released by the Aquaculture Stewardship Council (AAC) and the Ministry of Fishery. These requirements build on those of the AAC Standard (US) and Global Gap (Europe). The regime's characteristics are based on personal communications and scattered information in Indonesian grey literature. In addition to engaging in sustainable aquaculture management, landowners take part in mangrove rehabilitation. Apart from the mangrove rehabilitation, *eco-certified aquaculture* management is similar to that of *intensive aquaculture*. Shrimp seeds must be of native species and raised in natural hatcheries. No artificial feed is allowed and only natural pesticides are used for pest control.

Extensive aquaculture systems are usually rented by local smallholders. Limited infrastructure is required and pond dykes are made of mud. Managers rely on the tides to provide most of the food for the shrimp, but pesticides and fertilisers are added. Stocking occurs naturally or artificially with a low seed density. Remaining mangrove trees are frequently pruned and used for limited raw material use.

Compared to *extensive aquaculture, semi-intensive* production occurs with higher stocking rates and artificial seed. Earthen dykes are constructed, which require frequent maintenance. Water is exchanged artificially, and aeration occurs through pumping and using pedal wheels. Remaining mangrove trees are frequently pruned and used for limited raw material use.

Intensive aquaculture systems have developed infrastructure, hatchery and feeding systems. Pond owners use large quantities of food supplements and chemical fertilizers, pesticides and antibiotics. The stocking density is very high and ponds are protected by concrete dykes. Pedal wheels and pumps are used to control water flows. *Intensive aquacultureI* is less common as compared to semi-intensive aquaculture (Sualia et al., 2010).

4.5. Abandoned aquaculture

Abandoned aquaculture sites have been abandoned after unsustainable *aquaculture* exploitation, without plans or resources to

Table 5
Scores for ecosystem service provision in all mangrove management regimes in Java, Indonesia. Circles (●/○) indicate positive and diamonds (◆/◇) indicate negative ecosystem service provision, whereas a dash (-) indicates that no ecosystem service is provided. Closed shapes (●/◆) indicate high certainty and open shapes (○/◇) low certainty. Section 5.1 and Appendix C explain the underlying information for this table.

Main category	Scores for ecosystem service provision						
Specific management regime	Food	Raw materials	Carbon storage and sequestration	Coastal protection	Water purification	Nursery service	Recreation
Natural mangroves							
Protection	○○	●●●	●●●	○○○	●●●	○○○	○○○
Conservation	○○	●●	●●●	○○○	●●●	○○○	●●●
Low intensity use mangroves							
Production	○	●●	○○	○○	●●	○○	○○
Unprotected	○	○○	○○	○○	○○○	○○	○
High intensity use mangroves							
Plantation	●	●●	●●	○○	●●●	○○	○○
Silvo-fishery	●●	○	○	○	○○	○○	○○
Mangroves converted for aquaculture							
Eco-certified aquaculture	○○○	○	-	◇	◇◇◇	-	○
Extensive aquaculture	●●	○	◇◇	◇◇	◇◇	-	-
Semi-intensive aquaculture	●●	-	◇◇	◇◇	◇◇	-	-
Intensive aquaculture	●●●	-	◇◇	◇◇	◆◆◆	-	-
Abandoned aquaculture							
Abandoned aquaculture	-	-	◇	◇◇	◇◇	-	-

restore mangroves or *aquaculture* (Stevenson, 1997). We consider *abandoned aquaculture* a separate regime, because no formal management is in place. Reasons for abandonment include flood damage, shrimp disease and poor water quality (Stevenson, 1997). *Abandoned aquaculture* sites are difficult to generalise, due to difference in abandonment duration and intensity of former land uses. Remnants of concrete dykes and pumps may remain, and soils can be impacted due to traces from excess nutrient and pesticide use. Tree regrowth has not occurred and bare soil, water pools and shrubs mostly occupy the area. If managed and protected correctly, mangrove regeneration could be possible, depending on the pollution levels, inundation periods and inflow of mangrove seedlings (Stevenson, 1997).

5. Effects of management regimes on mangrove ecosystem services

5.1. Mangrove ecosystem service provision per management regime

All ecosystem service scores per management regime are integrated in Table 5. Below, we describe key information underpinning the scores per ecosystem service. More detailed information and references are provided in Appendix C. All scores in Table 5, except those for nature-based recreation, could be established in relation to the regimes' mangrove species richness, tree age, height and diameter, root length and, if applicable, structural diversity.

Quantitative information on natural fish and shrimp provision was based on studies by Gilbert and Janssen (1998), Kathiresan and Rajendran (2002), and Rönnbäck et al. (1999, 2007). Fish provision gradually decreases with decreasing mangrove age and species richness (from 1–1.6 ton ha^{-1} yr^{-1} in *protection* to 0.6 ton ha^{-1} yr^{-1} in *plantation*), but shrimp provision drops sharply when fewer than three mangrove species occur and the maximum tree age drops below 15 years (from 1 to 4 ton ha^{-1} yr^{-1} in *natural mangroves* to negligible in *plantation*). Note that few studies have quantified harvests in relation to mangroves and they merely provide indications for local harvests. Harvests in *silvo-fishery* and the *aquaculture* regimes (measured per area of pond) were based on Gilbert and Janssen (1998), Bengen (2003), Gautier (2002) and others (see

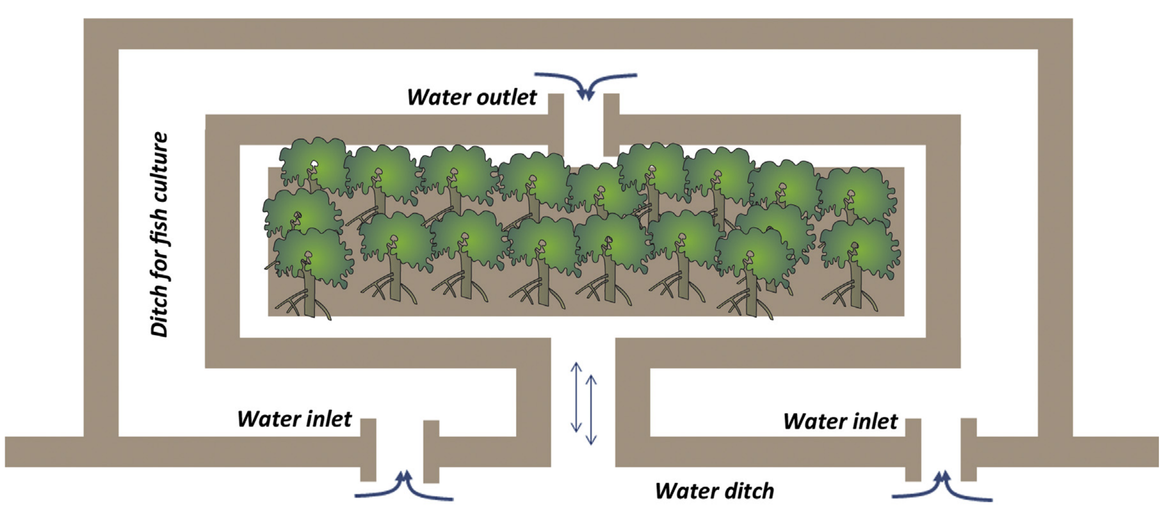

Fig. 3. 'Ideal' silvo-fishery option, with a two-gate water inlet system, a separate mangrove area inside the pond, and a separate ditch for fish. Source: Bengen (2003).

Appendix C). Shrimp yields of 1–3 ton ha^{-1} yr^{-1} were estimated for *silvo-fishery* and ranged from one to 7–15 ton ha^{-1} yr^{-1} for *extensive* and *intensive aquaculture*, respectively. Harvests of *eco-certified aquaculture* were based on the assumption that inputs are similar to *intensive aquaculture*.

Estimations of above-ground harvestable biomass and sustainable harvest were retrieved from studies of *Rhizophora* spp. dominated forests with similar management and ecological characteristics as our management regimes (e.g. Sukardjo and Yamada, 1992, Ong, 1993, Bosire et al., 2008, Kauffman et al., 2011). Only potential sustainable harvest numbers were available. Harvestable biomass for *protection* and *conservation* regimes was estimated at 150–300 and 90–250 ton ha^{-1} yr^{-1}, respectively, and corresponding maximum sustainable yields of 12–24 and 10–17 ton ha^{-1} yr^{-1}. The *production* regime scores similar to *conservation* due to the large age variability in *conservation* regimes. Biomass stocks of *plantation* and *silvo-fishery* regimes were 50–116 and 17–40 ton ha^{-1} yr^{-1}, respectively, but we assume that raw materials will only be harvested from the former (6–11 ton ha^{-1} yr^{-1}). Although biomass stocks of *extensive* and *eco-certified aquaculture* can be around 50 ton ha^{-1} yr^{-1}, only some deadwood and leaves will be actually harvested. No raw materials are available in the other *aquaculture* regimes.

Because of lacking data for carbon sequestration, we based the scores in Table 5 on carbon storage only. Data could be retrieved by matching tree age, height, diameter, species richness from studies by Sukardjo and Yamada (1992), Ong 1993, Alongi et al. (2008, 2012) and Kauffman et al. (2014) to the regimes' characteristics. However, we note the highly variable estimations, which is partly caused by differently measured soil depths or missing estimations for belowground carbon. Data of total carbon storage for Indonesia are scarce, but we estimated values ranging between 430 and 700 ton ha^{-1} for *protection* and *conservation*, with a higher variation within *conservation* regimes. Total carbon contents of *production* forests could reach 500 ton ha^{-1} (Kauffman et al., 2014), but this amount will be considerably lower due to timber harvesting impacts. Above-ground biomass would typically be around 100 ton ha^{-1} (Ong, 1993). Values for carbon storage by *plantation* and *silvo-fishery* regimes would, respectively, be up to 90 ton ha^{-1} and 40 ton ha^{-1}, but harvesting intensity and reliable soil carbon data could not be found. Pond owners in Java tend to drain their ponds at least twice a year and dig up soil to fortify their dykes. These activities will likely lead to considerable soil carbon losses (Kauffman et al., 2014). Ong (1993) found that carbon loss from oxidizing sediments can reach 75 ton ha^{-1} yr^{-1} in converted mangroves. All *aquaculture* regimes are assumed net emitters of carbon and therefore receive negative scores. Although sediment of *abandoned aquaculture* is unlikely to be dug up and reused, it will still continue to oxidise and leach carbon due to drainage (Ong, 1993, Kauffman et al., 2014).

Coastal protection has been poorly quantified, but we could score this service based on species richness, tree age and structural diversity per regime and assumptions on projected area. *Natural mangroves* can buffer impacts from waves and storm surges, assuming that their width exceeds the 500 m required for wave attenuation and several kilometres for storm surge reduction (Quartel et al., 2007, McIvor et al., 2012a). Wave attenuation can occur fully in *production* forests but storm surges could prevail because of timber extraction creating openings (Krauss et al., 2009). Wave attenuation can occur in *plantations*, but lacking mature mangroves, structural diversity and species richness is considered detrimental for storm surge protection. Although *silvo-fisheries* have some potential for small wave attenuation, impacts of higher waves and storm surges are likely to increase due to reduced projected area and dykes increasing the wave and surge height (Krauss et al., 2009, Winterwerp et al., 2013). This also holds true for *aquaculture* ponds, especially for *intensive aquaculture*. Winterwerp et al. (2013) showed that waves and storm surges reflect on concrete structures, thus increasing in height and removing sediments. Finally, we considered coastal protection by *eco-certified aquaculture* as ex-situ and therefore excluded this in the score as it generally involves establishing a greenbelt.

Most water purification studies have focused on mangroves with a species richness of 3–7 and an average age of at least 7 years (Robertson and Phillips, 1995, Gautier, 2002, Primavera et al., 2007). Therefore, the first five specific management regimes would be optimal for removing pollution from *semi-intensive* to *intensive aquaculture* effluent, provided that 2.4–9 ha and 3–21.4 ha of mangrove would be available for, respectively N and P removal (Robertson and Phillips, 1995). *Production* forests score lower because of sediment disturbance and, consequently, reduced ability to take up P (Li et al., 2008). Mangroves in *silvo-fisheries* could purify pond effluent, which contains less pollution compared to *aquaculture* (Bengen, 2003). All *aquaculture* options are considered emission sources of N and P in effluent water, due to high inputs and lacking mangroves inside ponds. Emissions range from 130 kg N and 40 kg P ha^{-1} yr^{-1} for *extensive aquaculture* to 200 kg N and 40 kg of P ha^{-1} yr^{-1} for *intensive aquaculture*. Emissions from *eco-certified aquaculture* are mostly similar to that of *intensive aquaculture*. Mangrove roots in any *aquaculture* regime are unlikely to contribute to water purification.

Fish and shrimp catches have been sporadically related to mangrove cover and even fewer studies have related the nursery service to management regime characteristics. We assume *natural mangroves* to be optimal nursery habitats for fish and crustaceans, due to high tree age, species richness and structural diversity, and presence of tall roots. Moreover, *natural mangroves* are embedded in complex, integrated coastal and/or estuarine ecosystems, which suggests intact hydrological and hydrodynamic cycles (Baran, 1999, Rönnbäck, 1999). The nursery service potential of *low intensity use* and *high intensity use* mangroves is assumed lower and more variable as compared to *natural mangroves*, especially for shrimp, due to increased disturbance and lower mangrove age, species richness and structural diversity. Kathiresan and Rajendran (2002) and others suggest that even with lower mangrove species richness and age, high amounts of fish but few shrimp could be expected. Water inlets, protection by dykes and mangroves in *silvo-fisheries* contribute to nutrient availability, refuge, shelter and clean water (Sofiawan, 2000, Bosma et al., 2014). The exact nursery contribution of *silvo-fisheries* has, however, never been quantified due to methodical difficulties (Sofiawan, 2000, Bengen, 2003). None of the *aquaculture* regimes provide nursery service.

Despite lacking data on mangrove-based recreation, we assume that the occurrence of high species richness, mature trees, and opportunities to fish make *natural mangroves* highly suitable for nature-based recreation. We also note the supporting role of mangroves for snorkelling and diving (Mathieu et al., 2003). Although recreation is only promoted and supported in *conservation* forests, we assume *protection* forests also important for nature-based recreation, because most activities would depend on or take place around the forests (Mathieu et al., 2003). Compared to *natural mangroves*, fewer places of interest occur in *low intensity use mangroves*, but fishing could still be an interesting recreational activity. *High intensity use mangroves* have potential for being of recreational interest, although only sporadic observations confirm this. Due to lacking natural features of interest to recreants, we assume no recreation service is provided in (*abandoned*) *aquaculture* regimes. Similar to *silvo-fisheries*, *eco-certified aquaculture* ponds could become recreation sites, because of their education and ecological interest.

Only 18 of all 77 scores (23%) in Table 5 are judged as 'certain', whereas the remaining 59 were considered 'uncertain'. Most certain results could be established for *plantations* and the *natural mangroves*. However, we note that relative differences of the obtained scores between management regimes could be established by consistently using the same set of ecological indicators for all management regimes.

5.2. Possible transitions between management regimes and effects on ecosystem services

Management decisions generally involve choices between management regimes and transitions from one regime to another (Ghazoul, 2007, Peña-Cortés et al., 2013). We used the summed-up scores from Table 5, thus weighing each ecosystem service equally, to illustrate possible effects of transitions between management regimes (Fig. 4). The findings in Fig. 4 should be treated with caution, because trade-offs between multiple management regimes and transitions between regimes over time have not been quantified yet in the literature and some transitions and regimes have not yet been observed in Java.

Mangrove conversion to *aquaculture* has occured over the last decades in Java (Sukardjo, 2009). Fig. 4 suggests that converting *natural mangroves* for *aquaculture* could lower ecosystem service scores from 20 to −4 (highest possible score = 30). This conversion can occur immediately, whereas natural regeneration, mangrove rehabilitation and, to some extent, aquaculture abandonment usually involve gradual and long-term processes. Aquaculture abandonment is a poorly studied transition (c.f. Stevenson, 1997), but Fig. 4 indicates that *abandoned aquaculture* systems (score −5) could eventually recover to regimes with high ecosystem service scores (20). Mangrove rehabilitation (i.e. from *aquaculture* to *silvo-fisheries* or *plantations*) could increase ecosystem service scores within up to ten years (−4 to 11 and 14, respectively).

Transitions between management regimes require additional investments, management activities and time, which were not explicitly considered in the analysis. Hence, we also did not consider the effects of mangrove conversion in our typology. Fig. 4 compares management regimes as 'steady states' and illustrates potential consequences of management decisions in mangrove systems. In the policy documents we consulted (Table 1), terms such as 'intensification', 'degradation', 'sustainable management' and 'rehabilitation' feature frequently but were often ill defined. Our findings show clear differences between management regimes, which can stimulate discussion on the consequences of and trade-offs involved in management decisions relating to transitions.

6. Discussion

Our paper integrates and relates multi-disciplinary information into policy-relevant findings and proposes a novel way to quantify management effects on ecosystem services. The following sections discuss the management regime typology, the ecosystem services assessment and the implications for decision making.

6.1. Management regime typology for analysing management effects on ecosystem services

Using management regimes to quantify management effects on ecosystem services has been proposed as a major research challenge for ecosystem services science (e.g. Carpenter et al., 2009). However, classifications of 'management regimes' in the literature lack consistent terminology and specific characteristics to describe management regimes unambiguously (e.g. Braat et al., 2008, De Groot et al., 2010, Van Asselen and Verburg, 2012). Most attempts to classify land-use intensities through management indicators (e.g. Alkemade et al., 2009, Verburg et al., 2013) are by global studies and, thus, use generic indicators.

Typologies of management regimes are rare in the literature, but many useful indicators and characteristics could be retrieved from studies of mangrove and aquaculture management. Together with the typology presented in Van Oudenhoven et al. (2015) for rangeland systems, this study is among the first to develop a methodology to develop management regimes that can be broadly applied to a region. The typology used the variation in national legislation and local management activities. Moreover, the easily measurable ecological characteristics served to both verify management regimes on location and to quantify ecosystem services based on the literature. This study's typology is firmly rooted in scientific literature and enables a consistent indicator-based

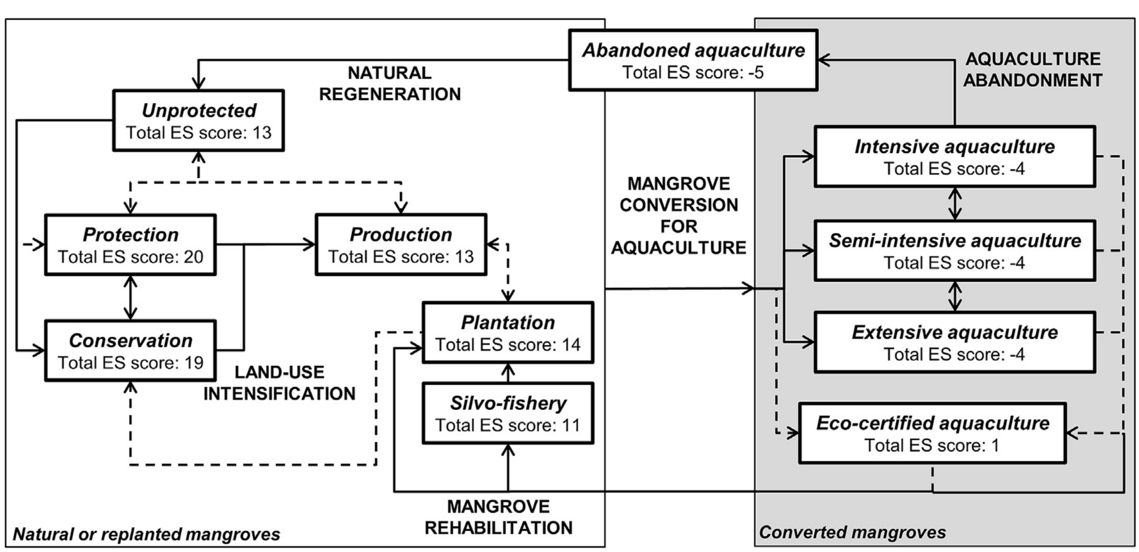

Fig. 4. Possible transitions between management regimes in mangrove systems in Java. Ecosystem service (ES) scores of Table 5 were added up for each management regime. They grey area on the right indicates mangroves converted for aquaculture and the white area on the left indicates natural or replanted mangroves. Dotted lines between regimes indicate transitions that could not be observed in Java yet. Terms in capital letters indicate transitions.

comparison of ecosystem service provision for multiple management regimes. Applying the typology in different mangrove regions would be possible with the same indicators, but would result in starker differences between regimes and, thus, the ecosystem services provided per regime.

Most of the typology's management regimes are recognized in government policies and occur frequently in Java (see references in Table 1 and Section 4). The regimes *unprotected mangroves*, *silvo-fisheries*, *eco-certified aquaculture* and, to some extent, *converted mangroves* deviate from the other regimes in this respect. *Unprotected mangroves* are not listed in official policy documents, but were observed throughout Java, especially where aquaculture had been abandoned due to coastal erosion. Our literature review yielded nine different *silvo-fishery* variations that are found throughout Indonesia (Appendix B). Interestingly, we found that the formally recognised silvo-fishery variations are unable to provide the required ecosystem services (Bengen, 2003, Sofiawan, 2000). *Silvo-fishery* is increasingly perceived as a sustainable alternative to aquaculture, but more quantitative research on ecosystem services in *silvo-fisheries* is needed to assess their potential as mangrove rehabilitation sites (Bengen, 2003, Bosma et al., 2014). The e*co-certified aquaculture* regime could contribute to coastal protection as ex-situ mangrove rehabilitation could strengthen greenbelts (McIvor et al., 2012a). Converted ecosystems have mostly been described as either intensive land-use systems (Verburg et al., 2013) or 'degraded' systems (Braat et al., 2008). Some argue that converted systems produce economic goods rather than ecosystem services (c.f. Schröter et al., 2014). We included *converted mangroves* in the typology because they are the main cause for mangrove decline and their outcomes should be compared to the benefits derived from differently managed systems to assess trade-offs between management decisions (Rönnbäck et al., 2003).

The typology captures important aspects that determine land-use and management decisions (Ghazoul, 2007, Peña-Cortés et al., 2013) but does not consider other important drivers of land use, management and ecosystem services, such as spatial extent, illegal activities and political instability. Most ecosystem services (e.g. coastal protection, nursery) require a minimum width and/or area of mangroves (McIvor et al., 2012a). However, such requirements could not be specified in the typology because of lacking spatial information in legal and scientific documentation. We assumed that management regimes in *natural* and *low intensity mangroves* would be sufficiently large to provide multiple ecosystem services. Comparing management regimes of different sizes could help to support these claims and would contribute to more informed spatial planning. We also did not account for illegal fishing and timber harvesting in the regimes. These practices will especially pressure *natural* and *low-intensity use mangroves* (Ewel et al., 1998, Walters, 2004). The political situation in Java is highly dynamic as legislations change swiftly and local legislation can be overturned by district or national legislation and vice versa (Sualia et al., 2013). However, we consider this more relevant for applying and monitoring management decisions than for this study's typology. The typology includes direct drivers and includes regimes that are considered realistic and long-lasting land-use purposes. Moreover, the typology is primarily a tool to analyse management effects on ecosystem services and not a precise account of Java's coastal systems and the services they provide.

6.2. Indicator-based analysis of ecosystem service provision per management regime

We integrated qualitative and quantitative information on ecosystem properties, and 'state' and 'performance' indicators of ecosystem services. Although some studies have reviewed indicators for multiple mangrove ecosystem services (e.g. Barbier et al., 2011), few have also applied the indicators in an ecosystem service assessment or linked them to ecosystem properties and management. We selected our indicators based on the scientific consensus on important ecosystem service indicators, rather than all available indicators. Because we limited our study to the ecosystem services literature, only few disciplinary studies were consulted. Ecosystem services science could benefit from integrating more ecological and biophysical research to assess and quantify underpinning ecosystem properties. More empirical evidence is also needed on the actual use and management of ecosystems and trade-offs between services. Most research is currently limited to drivers and state indicators rather than actual use (Rönnbäck et al., 2007, Walters, 2005b). Trade-offs between ecosystem services, such as between raw material harvest and carbon storage, and fishing and nursery service are also understudied (Alongi, 2012, Sheridan and Hays, 2003). Our analysis was limited by the selected ecosystem services, but this selection was made in dialogue with decision makers. We, consequently, ignored poorly studied but important other mangrove ecosystem services, such as other foods and medicinal resources (see Appendix A), water provision for *aquaculture*, salt water intrusion prevention and spiritual enrichment (Rönnbäck et al., 2007, Walters et al., 2008). Because these services are mostly provided in *natural* and *low intensity use mangroves*, we consider our current results underestimations of total ecosystem service provision in these management regimes.

Quantitative information on actual ecosystem services provision (i.e. use) is scarce for services, such as coastal protection, raw materials, nursery service and carbon sequestration. We related management indicators and ecological characteristics of management regimes with ecosystem service indicators and were able to 'transfer' data from other regions to Java. Moreover, combining qualitative and quantitative indicators enabled a comparison of service provision per management regime. Especially differences between regulating services are better explained by qualitative information because complex ecological processes underpinning service provision have not been sufficiently quantified. Our ecosystem service scores per regime integrate and quantify qualitative findings. If we had only considered quantitative indicators, our analysis would have excluded the coastal protection and nursery services, which are key for informing decision makers. Actual quantification of coastal protection and the nursery service could have been possible if we had followed a spatial approach, including local calibration of the models to do so. Time and budget restrictions excluded this option. The key indicators for assessing and monitoring the effects of management on ecosystem services were mangrove age (and related height, diameter etc.), species richness and, for some services, structural diversity. These indicators inform how ecosystem service provision per management regime could change over time.

Research on mangrove management and ecosystem services could benefit from more systematically integrating ecological research with land use, social, economic and land-use research (c.f. Peña-Cortés et al., 2013, Verburg et al., 2013). This integration is relevant because mangroves continue to be pressured by humans, and ecological research has been conducted for decades. Following our research approach (Fig. 1), future research should focus on quantifying linkages between management, ecosystem properties and mangroves' capacity to provide services and, finally, the socio-economic and cultural value of mangrove ecosystem services. Furthermore, our approach and the proposed management regime typology can facilitate the integrated valuation of more mangrove ecosystem services for diverse land-use purposes (Barbier et al., 2011).

Most ecosystem services research in mangroves has focused on comparing provision of few services (e.g. wood, shrimp and carbon storage) in two or three 'regimes'. Examples include *natural mangroves* compared to *plantations* (e.g. Bosire et al., 2008, Ong, 1993) and comparing different *aquaculture* systems (Gautier, 2002, Rönnbäck et al., 2003). Gilbert and Janssen (1998) analysed multiple ecosystem services provided through diverse 'management alternatives'. Based on a set of basic indicators, they suggested alternatives that correspond to the management regimes proposed here, such as 'preservation' (*conservation*) and 'aqua-silviculture' (*silvo-fishery*). The 'management alternatives' by Gilbert and Janssen (1998) formed spatially explicit scenarios, but were based on unclear methods and linked to very few indicators. Because Gilbert and Janssen (1998) based their final conclusions on the monetary value of marketed ecosystem services only, they conclude that *aquaculture* systems are the most preferred alternative, while *conservation* and *preservation* alternatives generate substantially less value. Our study compared all ecosystem services that were relevant for decision making and, consequently, 'valued' the importance of services such as coastal protection, carbon sequestration and water purification to be equally important as food and raw material provision.

6.3. Implications for decision making

Decision makers can assess the consequences of management decisions by considering the ecosystem services provided per regime. We integrated findings on multiple ecosystem services, most of which are currently not yet well understood by decision makers. An advantage of communicating the transitions between regimes would be that they occur relative quickly in mangroves, as compared to other ecosystems (Lewis, 2005). We integrated novel findings on understudied carbon emission (Kauffman et al., 2014) and wave height increase (Winterwerp et al., 2013) of *aquaculture* systems, which both suggest substantial risks. These risks could also be mitigated by 'hard management', such as constructing permanent aquaculture ponds and large dams surrounding the ponds. Such hard management practices involve considerable costs and require constant maintenance (Winterwerp et al., 2013), but could also enable *aquaculture* further inland rather than close to the coastline.

Within the 'Mangrove Capital' project, several co-authors and other project partners were together involved in updating the coastal management plan of Pangpang Bay, Banyuwangi (Fig. 2). Local decision makers were interested in how the area's current management would compare to situations in which sustainable aquaculture options, mangrove rehabilitation and protection would be promoted. Our study's findings contributed to a better shared understanding among decision makers and other stakeholders of the underpinning characteristics of mangrove ecosystem services. Moreover, decision makers have come to a shared vision that for the upcoming Pangpang Bay management plan, priority issues should include mangrove protection, mangrove-integrated aquaculture (*silvo-fishery*), protected and regulated fisheries, and ecotourism promotion. At the time of writing this paper, the priority issues had been selected into a broader local government programme aiming to create more jobs and help the region to grow economically. Despite the results' apparent scientific uncertainty (Table 5), the use of simple and tangible indicators for management and ecosystem services has clearly contributed to communicating about the ecosystem services of different management regimes. This positive outcome can be attributed to the fact that most relative differences in ecosystem services could be established based on the same indicators across different regimes.

Although our findings show the consequences of management decisions in terms of ecosystem services, current decisions are generally based on other criteria, such as economic returns, biodiversity protection and employment opportunities (Bosma et al., 2014, Peña-Cortés et al., 2013). We therefore recommend using a multi-criteria decision analysis to identify the optimal set of management regimes (Schwenk et al., 2012). For example, *aquaculture* systems provide food to many but economic returns to only a few individual managers and investors, whereas the disservices affect all stakeholders, including pond owners and local inhabitants. More balanced management decisions could be made if criteria such as ecosystem services, health, safety, employment were considered in addition to economic returns.

7. Conclusion

We analysed the effects of different management regimes on ecosystem services in Java's mangroves, to assess the consequences of management decisions. Our findings have provided decision makers with new and comprehensive information to make better, more informed decisions on coastal management. The management regimes represent clear options for decision makers, but we recommend conducting a multi-criteria decision analysis to identify the most desirable management regimes. Criteria could include ecosystem services, health, safety and employment.

Natural mangroves provide the most ecosystem services and score the best for all services except for fish and shrimp. Different intensities of *aquaculture* provide high amounts of fish and shrimp but this is due to artificial inputs and occurs at the expense of all other ecosystem services studied. Rehabilitation of *aquaculture* systems can reverse this loss of ecosystem services, while still providing shrimp or raw materials. The findings apply to Java, which had little remaining mangroves in the 1980s but saw a gradual recovery on locations where rehabilitation, natural regeneration or active protection occurred. Because mangrove ecosystem services depend mostly on mangrove tree age, species richness and structural diversity, our findings suggest that rehabilitation and long-term protection of mangrove systems can result in steadily increasing provision of multiple ecosystem services.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2015.08.003.

References

Aburto-Oropeza, O., Ezcurra, E., Danemann, G., Valdez, V., Murray, J., Sala, E., 2008. Mangroves in the Gulf of California increase fishery yields. Proc. Natl. Acad. Sci. U. S. A. 105, 10456–10459.

Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., ten Brink, B., 2009. GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems 12, 374–390.

Alongi, D.M., 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast Shelf Sci. 76, 1–13.

Alongi, D.M., 2012. Carbon sequestration in mangrove forests. Carbon Manag. 3, 313–322.

Baran, E., 1999. A review of quantified relationships between mangroves and coastal resources. Phuket Mar. Biol. Cent. Res. Bull. 62, 57–64.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.

Bengen, D.G., 2003. Introduction and Management of Mangrove Ecosystems. PKSPL-IPB, Bogor, Indonesia, p. 59.

Boon, P.I., Burridge, T.R., Fluker, M., 2002. A case for supply-led nature-based tourism within the marine and coastal temperate systems of South-Eastern Australia. J. Ecotourism 1, 93–103.

Bosire, J.O., Dahdouh-Guebas, F., Walton, M., Crona, B.I., Lewis III, R.R., Field, C., Kairo, J.G., Koedam, N., 2008. Functionality of restored mangroves: a review. Aquat. Bot. 89, 251–259.

Bosma, R.H., Nguyen, T.H., Siahainenia, A.J., Tran, H.T.P., Tran, H.N., 2014. Shrimp-based Livelihoods in Mangrove Silvo-aquaculture Farming Systems. Reviews in Aquaculture.

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J., Twilley, R.R., 2008. Mangrove production and carbon sinks: A revision of global budget estimates. Global Biogeochemical Cycles 22, GB2013.

Braat, L., ten Brink, P., Bakkes, J., Bolt, K., Braeuer, I., ten Brink, B., Chiabai, A., Ding, H., Gerdes, H., Jeuken, M., Kettunen, M., Kirchholtes, U., Klok, C., Markandya, A., Nunes, P., van Oorschot, M., Peralta-Bezerra, N., Rayment, M., Travisi, C., Walpole, M., 2008. The Cost of Policy Inaction: the Case of Not Meeting the 2010 Biodiversity Target (European Commission, Wageningen/Brussels).

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc. Nat. Acad. Sci. 106, 1305–1312.

Clough, B.F., Ong, J.E., Gong, W.K., 1997. Estimating leaf area index and photosynthetic production in canopies of the mangrove *Rhizophora apiculata*. Mar. Ecol. Prog. Ser. 159, 285–292.

Cochard, R., Ranamukhaarachchi, S.L., Shivakoti, G.P., Shipin, O.V., Edwards, P.J., Seeland, K.T., 2008. The 2004 tsunami in Aceh and Southern Thailand: a review on coastal ecosystems, wave hazards and vulnerability. Perspectives in plant ecology. Evol. Syst. 10, 3–40.

De Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex 7, 260–272.

Donato, D., Boone Kauffman, J., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4, 293–297.

Ewel, K.C., Twilley, R.R., Ong, J.E., 1998. Different kinds of mangrove forests provide different goods and services. Glob. Ecol. Biogeogr. 7, 83–94.

Farnsworth, E.J., Ellison, A.M., 1996. Sun-shade adaptability of the red mangrove, *Rhizophora mangle* (Rhizophoraceae): changes through ontogeny at several levels of biological organization. Am. J. Bot. 83, 1131–1143.

Gautier, D., 2002. The Integration of Mangrove and Shrimp Farming: A Case Study on the Caribbean Coast of Colombia. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 26 pages.

Ghazoul, J., 2007. Recognising the complexities of ecosystem management and the ecosystem service concept. GAIA 16, 215–221.

Giesen, W., Wulffraat, S., Zieren, M., Scholten, L., 2006. Mangrove Guide Book for Southeast Asia. FAO and Wetlands International, Rome.

Gilbert, A.J., Janssen, R., 1998. Use of environmental functions to communicate the values of a mangrove ecosystem under different management regimes. Ecol. Econ. 25, 323–346.

Jackson, C., Preston, N., Thompson, P.J., Burford, M., 2003. Nitrogen budget and effluent nitrogen components at an intensive shrimp farm. Aquaculture 218, 397–411.

Kathiresan, K., Rajendran, N., 2002. Fishery resources and economic gain in three mangrove areas on the south-east coast of India. Fish. Manag. Ecol. 9, 277–283.

Kauffman, J., Heider, C., Cole, T., Dwire, K., Donato, D., 2011. Ecosystem carbon stocks of micronesian mangrove forests. Wetlands 31, 343–352.

Kauffman, J.B., Heider, C., Norfolk, J., Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol Appl. 24, 518–527.

Knight, D., Mitchell, B., Wall, G., 1997. Bali: sustainable development, tourism and coastal management. Ambio 26, 90–96.

Komiyama, A., Ong, J.E., Poungparn, S., 2008. Allometry, biomass, and productivity of mangrove forests: a review. Aquat. Bot. 89, 128–137.

Komiyama, A., Santiean, T., Higo, M., Patanaponpaiboon, P., Kongsangchai, J., Ogino, K., 1996. Microtopography, soil hardness and survival of mangrove (*Rhizophora apiculata* BL.) seedlings planted in an abandoned tin-mining area. For. Ecol. Manag. 81, 243–248.

Krauss, K., Doyle, T., Doyle, T., Swarzenski, C., From, A., Day, R., Conner, W., 2009. Water level observations in mangrove swamps during two hurricanes in Florida. Wetlands 29, 142–149.

Kusmana, C., Istomo, Wibowo, C., Budi, S.W., Siregar, I.Z., Tiryana, T., Sukardjo, S., 2008. Manual of Mangrove Silvi-Culture in Indonesia. Directorate general of Land Rehabilitation and Social Forestry. Ministry of Forestry and KOICA. Jakarta, p. 217.

Lewis III, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24, 403–418.

Li, N., Chen, S., Zhou, X., Li, C., Shao, J., Wang, R., Fritz, E., Hüttermann, A., Polle, A., 2008. Effect of NaCl on photosynthesis, salt accumulation and ion compartmentation in two mangrove species, *Kandelia candel* and *Bruguiera gymnorhiza*. Aquat. Bot. 88, 303–310.

Macintosh, D.J., Phillips, M.J., Lewis III, R.R., Clough, B., 2002. Annexes to the: Thematic Review on Coastal Wetland Habitats and Shrimp Aquaculture. Case Studies 1-6. Report Prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium, Washington, DC.

Manson, F.J., Loneragan, N.R., Skilleter, G.A., Phinn, S.R., 2005. An evaluation of the evidence for linkages between mangroves and fisheries: a synthesis of the literature and identification of research directions. Oceanogr. Mar. Biol. 43, 483–513.

Massel, S.R., Furukawa, K., Brinkman, R.M., 1999. Surface wave propagation in mangrove forests. Fluid Dyn. Res. 24, 219.

Mathieu, L.F., Langford, I.H., Kenyon, W., 2003. Valuing marine parks in a developing country: a case study of the Seychelles. Environ. Dev. Econ. 8, 373–390.

Matthijs, S., Tack, J., van Speybroeck, D., Koedam, N., 1999. Mangrove species zonation and soil redox state, sulphide concentration and salinity in Gazi Bay (Kenya), a preliminary study. Mangroves Salt Marshes 3, 243–249.

Mazda, Y., Magi, M., Ikeda, Y., Kurokawa, T., Asano, T., 2006. Wave reduction in a mangrove forest dominated by *Sonneratia* sp. Wetl. Ecol. Manag. 14, 365–378.

McIvor, A.L., Möller, I., Spencer, T., Spalding, M., 2012a. Reduction of Wind and Swell Waves by Mangroves. Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit Working Paper 40. The Nature Conservancy and Wetlands International, Cambridge. UK, p. 27.

McIvor, A.L., Spencer, T., Möller, I., Spalding, M., 2012b. Storm Surge Reduction by Mangroves. Natural Coastal Protection Series: Report 2. Cambridge Coastal Research Unit Working Paper 41. The Nature Conservancy and Wetlands International, Cambridge, UK, p. 35.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9, 552–560.

Middelburg, J.J., Nieuwenhuize, J., Slim, F.J., Ohowa, B., 1996. Sediment biogeochemistry in an east African mangrove forest (Gazi Bay, Kenya). Biogeochemistry 34, 133–155.

Mumby, P.J., Edwards, A.J., Arias-González, J.E., Lindeman, K.C., Blackwell, P.G., Gall, A., Gorczynska, M.I., Harborne, A.R., Pescod, C.L., Renken, H., Wabnitz, C.C.C., Llewenyn, G., 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427, 533–536.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024.

Ong, J.E., 1993. Mangroves – a carbon source and sink. Chemosphere 27, 1097–1107.

Pauly, D., Ingles, J., 1999. The relationship between shrimp yields and intertidal vegetation (mangrove) areas: a reassessment. In: Yáñez-Arancibia, A., Lara-Domínguez, A.L. (Eds.), Ecosistemas de Manglar en América Tropical. Instituto de Ecología A.C., México, UICN/ORMA. NOAA/NMFS Silver Spring (MD), Costa Rica, pp. 311–318. USA.

Peña-Cortés, F., Rozas-Vásquez, D., Rebolledo, G., Pincheira-Ulbrich, J., Escalona, M., Hauenstein, E., Vargas-Chacoff, L., Bertrán, C., Tapia, J., Cisternas, M., 2013. Territorial planning for coastal zones in Chile: the need for geographical-environmental and natural risk indicators for spatial decision support systems. Int. J. Geosciences 4, 17–29.

Primavera, J., Altamirano, J., Lebata, M., Reyes, A.A., Pitogo, C., 2007. Mangroves and shrimp pond culture effluents in Aklan, Panay Is., Central Philippines. Bull. Mar. Sci. 80, 795–804.

Primavera, J.H., 1998. Mangroves as nurseries: shrimp populations in mangrove and non-mangrove habitats. Estuar. Coast Shelf Sci. 46, 457–464.

Puustinen, J., Pouta, E., Marjo, N., Tuija, S., 2009. Visits to national parks and the provision of natural and man-made recreation and tourism resources. J. Ecotourism 8, 18–31.

Quartel, S., Kroon, A., Augustinus, P., Van Santen, P., Tri, N.H., 2007. Wave

attenuation in coastal mangroves in the Red River Delta. Vietnam. J. Asian Earth Sci. 29, 576–584.
Robertson, A.I., Phillips, M.J., 1995. Mangroves as filters of shrimp pond effluents: predictions and biogeochemical research needs. Hydrobiologia 295, 311–321.
Rönnbäck, P., 1999. The ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecol. Econ. 29, 235–252.
Rönnbäck, P., 2001. Shrimp Aquaculture – State of the Art. Swedish EIA Centre, Uppsala.
Rönnbäck, P., Crona, B., Ingwall, L., 2007. The return of ecosystem goods and services in replanted mangrove forests: perspectives from local communities in Kenya. Environ. Conserv. 34, 313–324.
Rönnbäck, P., Troell, M., Kautsky, N., Primavera, J.H., 1999. Distribution pattern of shrimps and fish among *Avicennia* and *Rhizophora* microhabitats in the pagbilao mangroves, Philippines. Estuar. Coast Shelf Sci. 48, 223–234.
Rönnbäck, P., Troell, M., Zetterström, T., Babu, D.E., 2003. Mangrove dependence and socio-economic concerns in shrimp hatcheries of Andhra Pradesh, India. Environ. Conserv. 30, 344–352.
Satyanarayana, B., Bhanderi, P., Debry, M., Maniatis, D., Foré, F., Badgie, D., Jammeh, K., Vanwing, T., Farcy, C., Koedam, N., Dahdouh-Guebas, F., 2012. A socio-ecological assessment aiming at improved Forest resource management and sustainable ecotourism development in the mangroves of Tanbi Wetland National Park, the Gambia, West Africa. Ambio 41, 513–526.
Schrijvers, J., Gansbeke, D., Vincx, M., 1995. Macrobenthic infauna of mangroves and surrounding beaches at Gazi Bay, Kenya. Hydrobiologia 306, 53–66.
Schröter, M., van der Zanden, E.H., van Oudenhoven, A.P.E., Remme, R.P., Serna-Chavez, H.M., de Groot, R.S., Opdam, P., 2014. Ecosystem services as a contested concept: a synthesis of critique and counter-arguments. Conserv. Lett.
Schwenk, W.S., Donovan, T.M., Keeton, W.S., Nunery, J.S., 2012. Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. Ecol. Appl. 22, 1612–1627.
Sheridan, P., Hays, C., 2003. Are mangroves nursery habitat for transient fishes and decapods? Wetlands 23, 449–458.
Sofiawan, A., 2000. Sustainable mangrove utilization: developing silvofishery models, wetlands conservation newsletter. In: Wetlands International – Indonesia Programme, Bogor.
Spalding, M., Kainuma, M., Collins, L., 2010. World Atlas of Mangrove. Earthscan, London, UK.
Stevenson, N.J., 1997. Disused shrimp ponds: options for redevelopment of mangroves. Coast Manage. 25, 425–435.
Sualia, I., Ilman, M., Suryadiputra, I.N., 2010. Indonesian shrimp Sustainability. Status quo report. Coastal restoration and conservation programme – Indonesia. In: Wetlands international Indonesia programme, Bogor.
Sualia, I., Kuslati, E., Suryadiputra, I.N., 2013. Policy analysis of shrimp certification and development of sustainable shrimp farms. Original name (Indonesian): Analisis Kebijakan Sertifikasi Udang dan Pengembangan Tambak Berkelanjutan. In: Wetlands International – Indonesia Programme, Bogor, Indonesia.
Sukardjo, S., 2009. Mangroves for national development and conservation in Indonesia: challenges for the future. Mar. Res. Indones. 34, 47–61.
Sukardjo, S., Yamada, I., 1992. Biomass and productivity of a *Rhizophora mucronata* lamarck plantation in Tritih, Central Java, Indonesia. For. Ecol. Manag. 49, 195–209.
TEEB, 2010. The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations. Earthscan, London and Washington.
Van Asselen, S., Verburg, P.H., 2012. A land system representation for global assessments and land-use modeling. Glob. Change Biol. 18, 3125–3148.
Van Oudenhoven, A.P.E., Petz, K., Alkemade, R., Hein, L., de Groot, R.S., 2012. Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecol. Ind. 21, 110–122.
Van Oudenhoven, A.P.E., Veerkamp, C.J., Alkemade, R., Leemans, R., 2015. Effects of different management regimes on soil erosion and surface runoff in semi-arid to sub-humid rangelands. J. Arid. Environ. 121, 100–111.
Verburg, P.H., Asselen, S., van der Zanden, E.H., Stehfest, E., 2013. The representation of landscapes in global scale assessments of environmental change. Landsc. Ecol. 28, 1067–1080.
Vo-Luong, H.P., Massel, S.R., 2006. Experiments on wave motion and suspended sediment concentration at Nang Hai, can gio mangrove forest, Southern Vietnam. Oceanologia 48, 23–40.
Walters, B.B., 2004. Local management of mangrove forests in the Philippines: successful conservation or efficient resource exploitation? Hum. Ecol. 32, 177–195.
Walters, B.B., 2005a. Ecological effects of small-scale cutting of Philippine mangrove forests. For. Ecol. Manag. 206, 331–348.
Walters, B.B., 2005b. Patterns of local wood use and cutting of Philippine mangrove forests. Econ. Bot. 59, 66–76.
Walters, B.B., Rönnbäck, P., Kovacs, J.M., Crona, B., Hussain, S.A., Badola, R., Primavera, J.H., Barbier, E., Dahdouh-Guebas, F., 2008. Ethnobiology, socio-economics and management of mangrove forests: a review. Aquat. Bot. 89, 220–236.
Winterwerp, J.C., Erftemeijer, P.L.A., Suryadiputra, N., Eijk, P., Zhang, L., 2013. Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. Wetlands 33, 515–526.
Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., Smith III, T.J., 2012. The role of mangroves in attenuating storm surges. Estuar. Coast Shelf Sci. 102–103, 11–23.