Climate Risk Management 12 (2016) 69–82

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

The Asset Drivers, Well-being Interaction Matrix (ADWIM): A participatory tool for estimating future impacts on ecosystem services and livelihoods

T.D. Skewes [a,*], C.M. Hunter [b], J.R.A. Butler [c], V.D. Lyne [a], W. Suadnya [d], R.M. Wise [e]

[a] *CSIRO Oceans and Atmosphere Flagship, GPO Box 2583, Brisbane, QLD 4001, Australia*
[b] *College of Marine and Environmental Sciences, James Cook University, PO Box 6811, Cairns, QLD 4870, Australia*
[c] *CSIRO Land and Water Flagship, GPO Box 2583, Brisbane, QLD 4001, Australia*
[d] *Faculty of Agriculture, University of Mataram, Jl. Majapahit 62, Mataram 83127, Nusa Tenggara Barat Province, Indonesia*
[e] *CSIRO Land and Water Flagship, Black Mountain, Canberra, ACT 2911, Australia*

A R T I C L E   I N F O

Article history:
Available online 11 September 2015

Keywords:
Adaptation
Climate change
Population growth
Human well-being
Indonesia
Valuation

A B S T R A C T

Building an effective response for communities to climate change requires decision-support tools that deliver information which stakeholders find relevant for exploring potential short and long-term impacts on livelihoods. Established principles suggest that to successfully communicate scientific information, such tools must be transparent, replicable, relevant, credible, flexible, affordable and unbiased. In data-poor contexts typical of developing countries, they should also be able to integrate stakeholders' knowledge and values, empowering them in the process. We present a participatory tool, the Asset Drivers Well-being Interaction Matrix (ADWIM), which estimates future impacts on ecosystem goods and services (EGS) and communities' well-being through the cumulative effects of system stressors. ADWIM consists of two modelling steps: an expert-informed, cumulative impact assessment for EGS; which is then integrated with a stakeholder-informed EGS valuation process carried out during adaptation planning workshops. We demonstrate the ADWIM process using examples from Nusa Tenggara Barat Province (NTB) in eastern Indonesia. The semi-quantitative results provide an assessment of the relative impacts on EGS and human well-being under the 'Business as Usual' scenario of climate change and human population growth at different scales in NTB, information that is subsequently used for designing adaptation strategies. Based on these experiences, we discuss the relative strengths and weaknesses of ADWIM relative to principles of effective science communication and ecosystem services modelling. ADWIM's apparent attributes as an analysis, decision support and communication tool promote its utility for participatory adaptation planning. We also highlight its relevance as a 'boundary object' to provide learning and reflection about the current and likely future importance of EGS to livelihoods in NTB.

* Corresponding author. Tel.: +61 7 3833 5963.
E-mail addresses: tim.skewes@csiro.au (T.D. Skewes), cass.hunter@jcu.edu.au (C.M. Hunter), james.butler@csiro.au (J.R.A. Butler), iwsuadnya@hotmail.com (W. Suadnya), russell.wise@csiro.au (R.M. Wise).

http://dx.doi.org/10.1016/j.crm.2015.08.001
2212-0963/

Introduction

Rural communities in developing countries have a high reliance on local ecosystems to supply goods and services which support their livelihoods and contribute significantly to their well-being (Butler et al., 2014a). The current and future status of these ecosystem goods and services (EGS), and the resulting impact on well-being is therefore important for planning adaptation strategies designed to redress social-ecological systems' vulnerability to threats such as climate change and human population growth (Reed et al., 2013).

For communities to effectively plan and appropriately respond to future threats to their well-being there is a requirement for decision-support tools and information that are relevant and accessible to them and other stakeholders, and clearly explain the sources of future impacts (Kirono et al., 2016). More broadly, for expert-driven models to communicate science outputs, tools must be transparent, credible, and unbiased (Cash et al., 2003; Bagstad et al., 2013). Also, because adaptation policies are continually revised as updated data, models and projections become available, tools must be replicable, affordable and flexible enough to incorporate new knowledge into iterative decision-making (Webster et al., 2003; Wise et al., 2014).

Achieving these principles is challenging. Complex computational simulation models of social-ecological systems are typically the 'gold standard' for providing the most accurate projections of future system states under various scenarios (Plagányi et al., 2011). However, these approaches are often resource- and data-intensive, and have restricted application as only a few experts can follow the procedures. This excludes the lay person from the important learning and capacity building derived from analysis and reflection (Cash et al., 2006; Gidley et al., 2009). Furthermore, the detailed information required to populate such 'whole of system' models is often lacking or scant (Nelson et al., 2010; Dorward, 2014).

These challenges are acute in developing countries, where even data on primary EGS (e.g. agriculture and fisheries production) are often scattered, non-existent or inaccessible. Consequently, it is difficult to determine the potential impact that future climate and development scenarios will have on human well-being, exacerbating the vulnerability of resource-dependent communities (Ensor, 2011). A solution necessitates the integration of disparate data sources, augmented by experts' and local stakeholders' knowledge, often elicited relatively rapidly through participatory processes (Butler et al., 2014b). While perhaps sub-optimal from a purely scientific perspective, this approach has the benefit of empowering local stakeholders, and considering their knowledge and values through the process (Butler et al. 2015, 2016a,b,c).

In this study we demonstrate an approach for the assessment of cumulative impacts on livelihoods in a timely and transparent manner based on a novel participatory tool – the Asset Drivers Well-being Interaction Matrix (ADWIM) – which facilitates the integration of scientific and local knowledge. It is designed for data-poor situations, where stakeholder input is necessary to fill gaps in secondary data, and also to engage and empower them. Using Nusa Tenggara Barat Province (NTB), Indonesia, as an example, and as part of the multi-stakeholder participatory planning process described in this special issue (Butler et al. 2016a,b,c), we describe the tool and illustrate how it is sufficiently flexible to produce estimates of potential impact to EGS and human well-being for different locations of interest, enabling priority-setting at multiple scales. Based on our experiences of applying ADWIM in NTB, we discuss its assumptions and limitations, and its strengths and weaknesses relative to principles of effective science communication and ecosystem services modelling.

Methods

Study area

Nusa Tenggara Barat Province (NTB) is located in the island archipelago of eastern Indonesia (Fig. 1). The province consists of two large islands, Lombok (4725 km^2) and Sumbawa (15,448 km^2), which feature the volcanoes of Mount Rinjani and Mount Tambora. Due to the orographic effects of the volcanoes, steep climate gradients exist across the islands (Kirono et al., 2016; McGregor et al., 2016). Combined with variations in soil type, these micro-climates support diverse agricultural systems (Yasin et al., 2007) and results in a diversity of rural livelihoods which can vary over relatively short distances (Butler et al., 2014a).

At the time of the study in 2010–2012, the province was administratively divided into 8 rural districts (kabupaten) and 105 rural subdistricts (kecamatan; Fig. 1). Rural subdistricts ranged in area from 13.1 km^2 to 763.9 km^2, and their populations ranged from 2717 to 100,105 people.

Units of analysis

The adaptation planning process consists of three stages which combine 'top-down' with 'bottom-up' assessments of community vulnerability and adaptation needs, and applied the subdistrict as the administrative unit of analysis (Butler et al., 2015, 2016a,b,c). The process begins by analysing adaptation needs from the 'top-down' perspectives of government and other provincial level stakeholders based on future scenario planning. A 3-day scenario planning workshop was held where the 105 rural subdistricts were aggregated through a typology which clustered them into seven types based on EGS utilisation (Rochester et al., 2016). The output of this workshop was adaptation strategies designed for each of the subdistrict types. A similar 2-day 'bottom-up' scenario planning workshop was then held in each case study subdistrict to

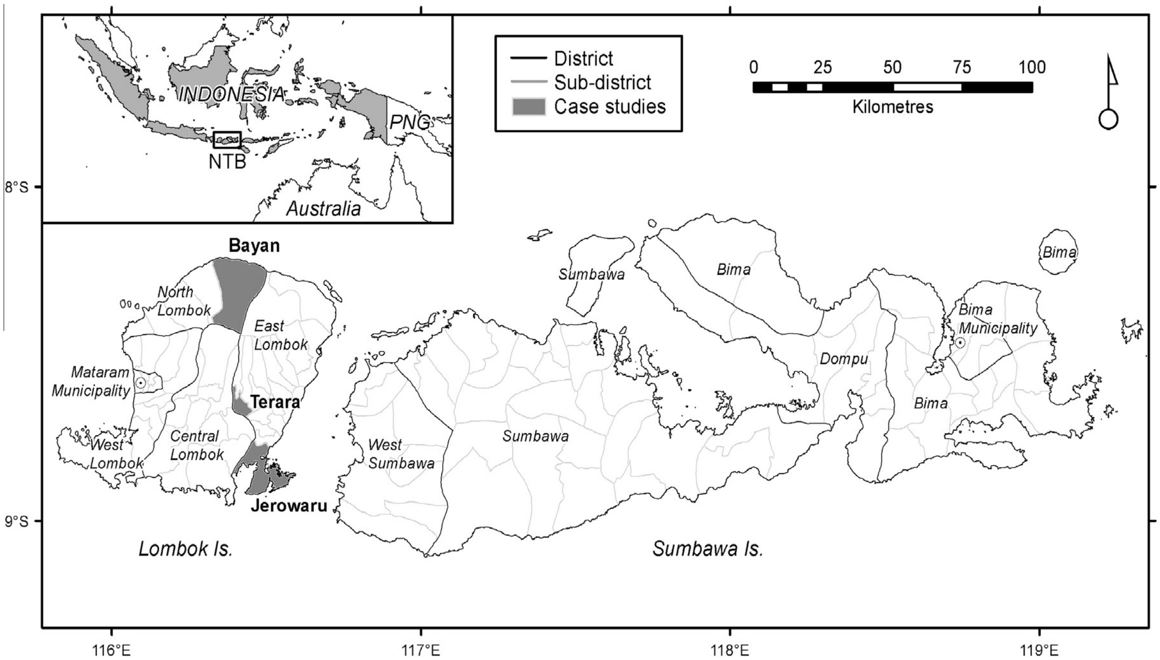

Fig. 1. Nusa Tenggara Barat Province (NTB), eastern Indonesia. Also shown are the administrative boundaries for districts and subdistricts. Locations of Jerowaru, Terara and Bayan case study subdistricts are shown.

engage local level stakeholders and identify adaptation strategies for each subdistrict. These were later followed by integration workshops which combined the outputs from both scenario planning workshops.

ADWIM was applied as part of the scenario planning workshop processes to analyse potential impacts of the 'Business as Usual' development scenario on EGS and human well-being, first for the subdistrict types, and then for the case study subdistricts. All workshops were facilitated by a local Indonesian faciliator and conducted in Bahasa Indonesia.

ADWIM approach

The approach focuses on the causal links between drivers of change, stressors, ecosystem assets (EAs), EGS and human well-being. These terms are defined in Table 1.

ADWIM consists of matrices of interactions between these components built into Microsoft Excel spreadsheets. Interactions are calculated through two sequential steps (Fig. 2). Step 1 includes the collation of data prior to participatory planning workshops. These workshops are used to build assessments of cumulative impacts from drivers and stressors on EGS (Fig. 2a). The assessments are based on scientific literature and expert opinion (described below). Step 2 involves valuation of EGS by stakeholders during workshops using semi-quantitative scoring, and the real-time integration of interactions from

Table 1
Definitions used in ADWIM.

Term	Definition
Drivers (system)	Following the Millennium Ecosystem Assessment (2005, p. 87), drivers are "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem"
Stressors	The attribute of a driver that directly causes change to an ecosystem asset
Ecosystem assets	The animal and plant populations and their supporting habitats which provide the flows of ecosystem goods and services and stocks of unutilised natural capital
Ecosystem goods and services	The flows of goods and services provided by ecosystem assets which are actually and directly valued and consumed by people (Wallace, 2007; Kent and Dorward, 2012). This combines the Millennium Ecosystem Assessment's (2005) classification of 'provisioning' ecosystem services (products obtained from ecosystems) and 'cultural' ecosystem services (non-material benefits), but ignores 'regulating' (benefits obtained from the regulation of ecosystem processes) and 'supporting' services (those necessary for the production of all other ecosystem services)
Human well-being	Following the Millennium Ecosystem Assessment (2005), well-being is the fulfilment of peoples' basic need to live a healthy life, including income, health, food security, social cohesion and freedom of choice. We simplified this to four indicators: income, health, food security and culture, of which the first three are core components of the Millennium Development Goals United Nations (2014)

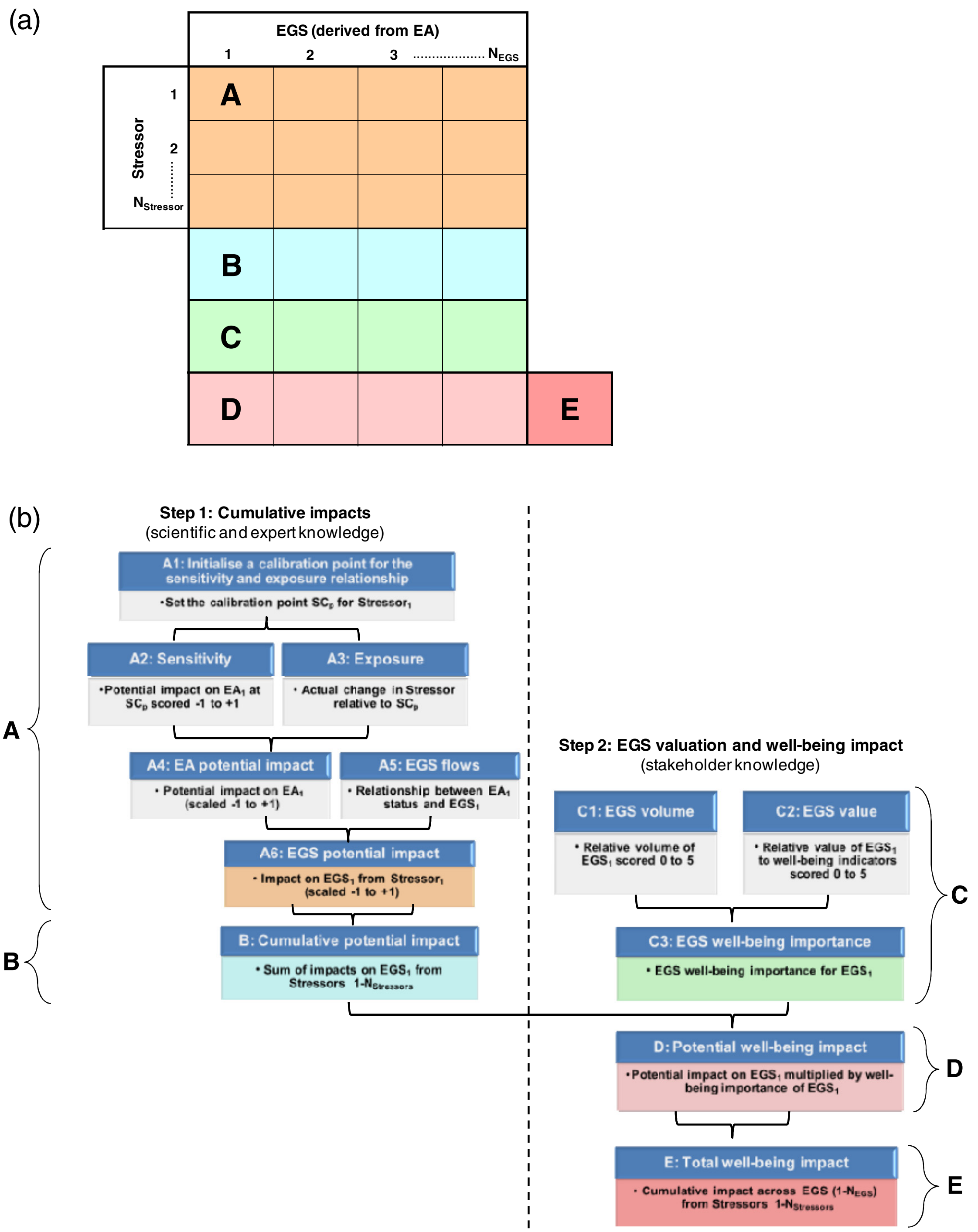

Fig. 2. The ADWIM process illustrated for interactions showing (a) the design of the matrix and (b) the two analytical steps and the knowledge incorporated. Note that example cells labelled A–E in (a) correspond to calculations A–E in (b). SC_p is stressor calibration point: EA is ecosystem asset: EGS is ecosystem goods and services.

Step 1 to analyse potential impacts on human well-being at three time horizons: 2030, 2060 and 2090 (Fig. 2b) (described below).

Step 1: Cumulative impacts

Data on system drivers and stressors and ecosystem assets of NTB were collated prior to the first provincial level scenario planning workshop. A workshop was held with NTB experts (e.g. local researchers, government agency officers) to elicit information and fill knowledge gaps. If available, spatial datasets were collated in a GIS.

System drivers and stressors

Two primary drivers of change, climate change and human population growth, were considered. For climate change, the related stressors considered were surface and sea surface temperature, wind speed and direction, storms and cyclones, ocean current patterns, rainfall, sea level and ocean pH (i.e. acidification). For human population growth, the related stressors were resource exploitation, land conversion and pollution. Much of this information was presented in the opening sessions of each workshop which examined drivers of change for livelihoods (see Butler et al., 2016).

For climate change stressors, future changes in surface and sea surface temperature, wind direction and strength and rainfall were estimated from 20 year averages of the CSIRO Conformal Cubic Atmospheric Model (CCAM) using the SRES A2 'Business as Usual' emissions scenario and downscaled to NTB based on a 14 km grid (Kirono et al., 2016; McGregor et al., 2016). At the time of the analysis this was considered to be the most likely emissions scenario (IPCC, 2007). Sea level rise inundation was estimated from an analysis of satellite derived elevation data for NTB (Farr et al., 2007) and sea level rise estimates from the Lombok Vulnerability Assessment (MoE, 2010). Changes to ocean pH, storm and cyclone frequency and severity, and ocean current patterns were gathered from the scientific and grey literature for the region. Projections of future climate change stressors were estimated for each subdistrict.

For population growth, projections were based on the most recent 2010 census data and the medium variant of the United Nation's cohort-component method (United Nations, 2002), which indicated that NTB's population could increase from 4.5 million in 2010 to 6.4 million in 2050 (41%), and 6.9 million by 2100 (Fachry et al., 2011). Population projections were estimated for each rural subdistrict by applying the equivalent growth rates for NTB districts over the time period concerned to the local 2010 census data. Land conversion was estimated from land use maps of NTB and GIS analysis. An existing land use map for 2007 was obtained from Indonesia's National Land Agency (BPN), created from classified LandSat 7 remote sensed data of NTB and supervised classification, to produce a map with several land use categories including urban land, agricultural land, wetland and forest coverages. We then buffered the urban "footprint" so that its coverage increased proportionally to population growth for the various future time periods. This buffered urban footprint was then used to calculate the relative loss of agricultural and other land classes for the three population growth scenarios. Resource exploitation and pollution were also assumed to have a directly proportional relationship with population growth.

Ecosystem assets (EA)

A preliminary list of EGS utilised by communities in NTB was formulated from interviews with local resource scientists and key community stakeholders (Rochester et al., 2016). This was then used to formulate a list of EA, being the biotic populations that directly supply the EGS, and their supporting habitats and biotic communities. Descriptions of the region's EA and habitats were collated from the scientific and grey literature and from local experts. For each EA, information was collated on its current status, approximate area, location, and relationships to other EAs and system drivers and stressors.

EGS potential impact

The first calculation represented in the matrix (A; Fig. 2) was the estimation of potential impact of stressors on each EGS, based on steps A1 to A6.

A1: A stressor calibration point (SC_p) was established to initialise the theoretical relationship between the level of a stressor change and the status of ecosystem assets (EA). The SC_p was usually selected to represent the "worst case" actual stressor changes in NTB, and usually approximated the maximum change in the stressor projected at the furthest time horizon (i.e. 2090). In the case of non-linear responses in a stressor (e.g. the status of a biotic population in response to temperature changes), separate SC_p scores were defined for each time-step in the assessment (i.e. 2030, 2050 and 2090).

A2: The sensitivity of and EA was estimated as the potential cumulative impact (i.e. change in status) caused by the change in the stressor set by SC_p, taking into account the effect of the stressor on the EA directly, and also on its supporting habitats and trophic considerations. Sensitivity was scored between −1 to +1. A score of −1 indicated absolute loss or degradation. A score of zero indicated a zero or neutral effect. A maximum positive score of +1 indicated absolute increase or enhancement. Sensitivity scores were based on available published scientific and expert opinion, and the information used to reach the consensus score was recorded as a summary narrative, with referenced sources and names of experts consulted.

A3: Exposure was the estimated projected future change in the stressor, relative to the stressor calibration point (SC_p). Exposure levels were averaged across the spatial unit of analysis (e.g. sub-district) to account for spatial differences. For each stressor this produced a degree of change for the three future time steps (2030, 2050, 2090). In the case of climate-driven stressors, the degree of change was taken from the present day to the time step concerned. For population-related stressors, exposure was estimated to be a function of relative population growth.

A4: The potential impact on an EA was calculated as the product of the relative scores of sensitivity for each EA (A2) and the exposure related to the stressor in the area of investigation (A3).

A5: The EA-EGS flows defined the relationship between changes in EA and EGS. This acknowledges that EGS provision to humans does not always vary in a directly proportional way with EA status – for example this could include thresholds where an EA might be degraded to a level where EGS flow ceases (such as when it becomes economically unviable to fish at low fishing density). While we acknowledge this relationship in the model, in this case, we assumed a proportional relationship between EA status and EGS volume. This assumption is probably reasonably valid as, in the case in many poor rural settings, exploitation continues even when the resource status is much degraded.

A6: The potential impact on an EGS is then calculated as the EA potential impact (A4) and modified by the EGS flow relationship (A5). The potential impact was a semi-quantitative score ranging from −1 (absolute degradation of the EGS) to +1 (absolute enhancement of the EGS), with 0 implying a neutral effect.

The cumulative potential impact on each EGS (B; Fig. 2) was then calculated by summing each of the stressors' potential impact scores.

Step 2: EGS valuation and well-being impact.

EGS well-being importance

The relative importance of all EGS to a community's well-being, or at least that component of wellbeing that relies on local EGS, was estimated at each scenario planning workshop. The calculation is represented in the matrix (C; Fig. 2) and was based on steps C1 to C3.

C1: Workshop participants, individually or in small groups, scored each EGS's relative volume on a semi-quantitative scale of 0 (none) to 5 (greatest volume). To facilitate the scoring, participants were asked to consider the highest volume EGS first and to score this 5, and then to score all other EGS relative to this.

C2: Workshop participants then scored each EGS' relative value against the four indicators of well-being (income, health, food security and culture) using a scale from 0 (no value) to 5 (highest value). Participants were asked to consider the value of each EGS as if they had the same quantity of each EGS (e.g. 1 tonne) and then to score the highest value EGS first and to score this 5, and then to score all other EGS relative to this. The overall value of an EGS was the addition of the four separate indicator scores.

C3: The well-being importance for each EGS was calculated as the product of the volume score and the sum of the indicator values scores. The raw importance scores were then standardised such that the importance of each EGS was relative to the total EGS importance scores, and represented as a percentage of the overall EGS-based wellbeing Importance. This scaled the importance of each EGS relative to the overall EGS-derived well-being for the community.

Potential well-being impact

The potential well-being impact for each EGS was then calculated (D; Fig. 2) by multiplying the cumulative potential impact on the EGS (calculation B) with the well-being importance (calculation C). This weights potential impacts on EGS in terms of their well-being importance.

Total well-being impact

Total well-being impact was then calculated (E; Fig. 2) by summing the cumulative well-being impact across all EGS. Most of these analyses were carried out during the workshop, in near real time, by inputting the participant's scores into prepared spreadsheets. The final results were presented to workshop participants to assist with the formulation of adaptation strategies so that they could address the impacts of future scenario on the communities' natural resource base (see Section Results).

Assumptions

ADWIM makes seven explicit assumptions

Assumption 1: Constant management and utilisation patterns. It is assumed that current management practices and EGS utilisation patterns remain constant between the present and each of the future time horizons. Management responses or use of alternative EGS are considered as potential adaptation strategies in following sessions of the workshops (Butler et al., 2016c; Wise et al., 2016). The artifice of this assumption was partially mitigated by focussing discussion on the results for the 2030 time horizon. Because of the short time frame (i.e. 18 years from the present), the current portfolio of EGS is unlikely to alter significantly, and their production, harvesting and management regimes are also unlikely to have changed drastically.

Assumption 2: Constant values of EGS. As for Assumption 1, it was assumed that the values of EGS in terms of well-being indicators remain the same at future time horizons as for today and that effectiveness of actions remains the same in the future.

Assumption 3: EGS potential impacts are based on stressors within the spatial unit of analysis. It was assumed that the EGS listed for any spatial unit of analysis flowed from EAs within that unit of analysis. Hence EGS sourced from outside the unit of analysis, and the potentially different impacts of climate and population-derived stressors on these EGS were not considered.

Assumption 4: Averaged climate stressors. Changes to climate drivers and stressors were generally expressed as 20 year averages per annum, and therefore did not account for extreme events (McGregor et al., 2016). However, it was possible to apply estimated changes in the onset of seasonal rainfall, and hence related impacts on crops (Kirono et al., 2016).

Assumption 5: Additive impacts of multiple stressors on EGS. ADWIM sums the impacts of a range of stressors on EGS, and therefore assumes an additive effect amongst stressors. This assumes that there are no synergistic (amplified stress) or antagonistic (reduced stress) effects between stressors.

Assumption 6: Linear relationships between EA condition and EGS flow. The assumed relationship between the flow of an EGS and the condition of the underlying EA was linearly proportional. Possible non-linear relationships and threshold effects between the condition of an EA and the flow of an EGS were not considered.

Assumption 7: Linear relationship between population density and land conversion. It was assumed that the area of agricultural land converted to urban or related infrastructure would increase in a directly proportional relationship with population density. This assumed that housing density would remain constant.

Results

Examples of ADWIM outputs for 2030 are shown from the provincial level workshop (where several typologies of subdistricts were analysed, Rochester et al., 2016), and subsequent subdistrict level workshops (where more detailed information was gathered from local stakeholders). These were labelled and explained in Bahasa Indonesia, but are presented here in English.

Provincial analysis

The first output was a comparison of EGS well-being importance and EGS potential impacts for each natural resource typology for NTB (Rochester et al., 2016). For Type 1, the three most important EGS were inshore coastal fish, offshore pelagic fish and wetland rice production (Fig. 3). For Type 5, wetland rice was the most important, followed by cattle and tobacco production (Fig. 4). By 2030, potential impacts on EGS in both subdistrict types were largely negative, although there were some positive impacts from temperature and rainfall change (Fig. 3, Fig. 4). In Type 1, climate and population-driven stressors contributed similarly to negative impacts on most EGS, and rainfall decline was an influential stressor for many cultivated and freshwater-derived EGS (Fig. 3). By comparison, negative impacts for Type 5 were dominated by population-driven stressors, and land conversion was the most influential stressor for cultivated EGS (Fig. 4).

The second output was a comparison of the total well-being impact for each of the seven subdistrict types at the 2030, 2060 and 2090 time horizons (Fig. 5). By 2030 and 2060, Type 7 will be the most impacted. However, by 2090 Type 3 will become the most impacted. For all types the negative impacts increased from one time horizon to the next, but not in a linear fashion due to local variations in climate change and population densities.

Subdistrict analysis

Examples of two subdistrict case studies are shown: Jerowaru subdistrict within Type 1, and Terara subdistrict within Type 5 (Fig. 5). For Jerowaru the three most important EGS were maize, buffalo and cattle (Fig. 6). Population-driven stressors dominated the highest negative impacts by 2030, with some impacts also from declining rainfall (Fig. 6). By comparison, in Terara the most important EGS were rice production, chickens and tobacco, and rice was almost twice as important as chickens (Fig. 7). As for Jerowaru, population-driven stressors dominated the highest negative impacts by 2030, with climate-driven impacts were less influential.

When these subdistrict assessments are compared to the broader analysis of their subdistrict type, some important differences emerge. For Type 1 (Fig. 3), the three most important EGS were inshore coastal fish, offshore pelagic fish and wetland rice production, but for Jerowaru, of these, only offshore fish was listed in the most important 30 EGS (Fig. 6). The discrepancy between Type 5 (Fig. 4) and Terara (Fig. 7) was less evident, with rice production being the predominant EGS in both. The potential negative influences of climate and population-driven stressors were also similar between the type and subdistrict analyses.

Discussion

By focusing on the causal linkages between drivers of change, stressors, EAs, EGS and well-being, ADWIM builds on growing recognition of the ecosystem services concept as a platform for viewing linked social-ecological systems, and its utility for science and management (Daily et al., 2009; Villa et al., 2014). This follows from the Millennium Ecosystem Assessment (MA, 2005), which promoted ecosystems as vital assets, and recognised the central role they play in supporting human well-

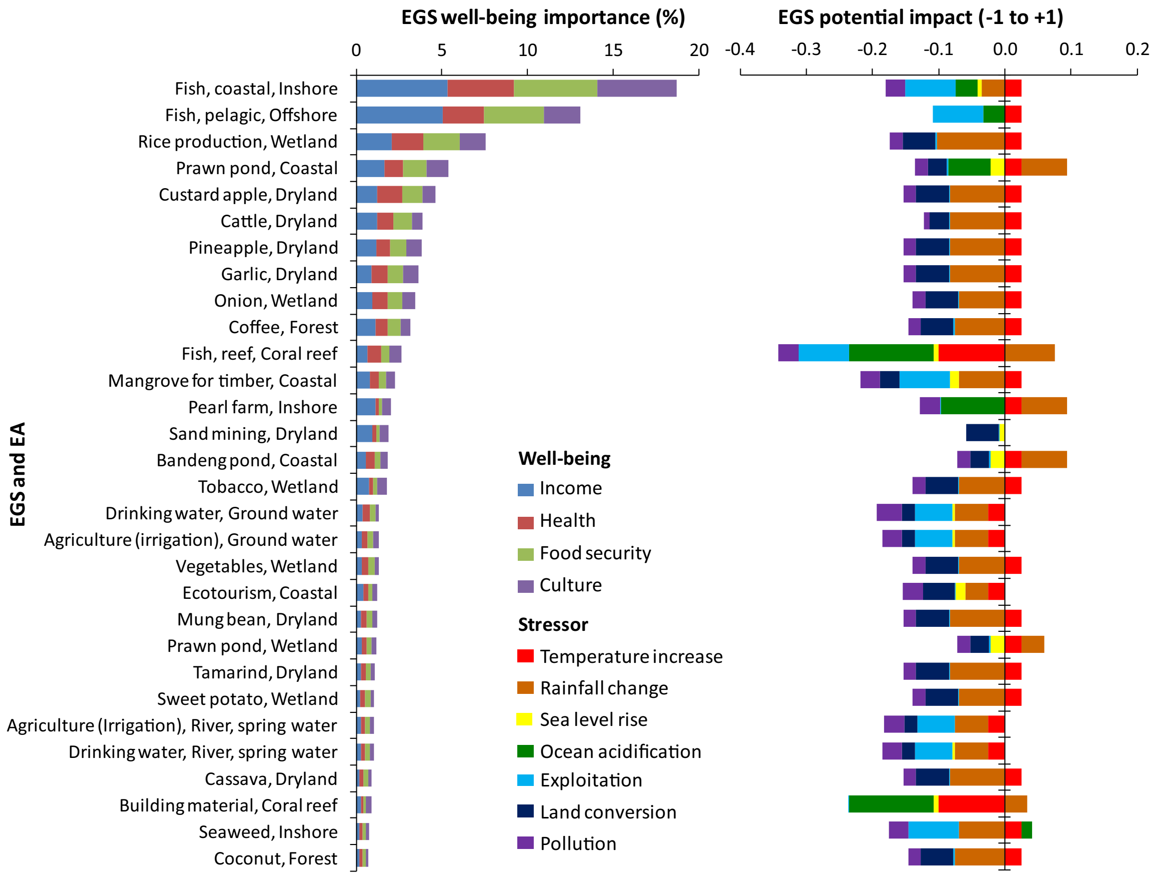

Fig. 3. Ecosystem goods and services (EGS) and their supporting ecosystem asset (EA) in Type 1 of the provincial subdistrict typology, showing their well-being importance in terms of income, health, food security and culture (left). Potential impacts in 2030 (right) are shown for each EGS in terms of stressors from climate change and population growth. Only the 30 most important EGS are listed.

being today and in the future (Daily et al., 2009). This triggered the development of decision-support tools that assess, quantify, model, value, or map multiple ecosystem services in land and seascapes. A comparative assessment of 17 tools by Bagstad et al. (2013) found that the majority were focused on mapping ecosystem services. However, none were designed to estimate potential future impacts from climate change and human population growth on ecosystem services and livelihoods to manage social-ecological systems and inform adaptation, or to integrate scientific and stakeholder knowledge in data-poor situations. Hence ADWIM represents an original contribution to the nexus between ecosystem services modelling and participatory adaptation planning.

According to Harley et al. (2006) most vulnerability assessments have often only focused on interactions between single climate change variables and single habitats, species or species groups. Chin et al. (2010) progressed this approach by constructing a matrix of semi-quantitative vulnerability scores for shark and ray species to multiple climate change stressors. Our matrix design advances this approach by considering the impact of multiple climate and human population-driven stressors on multiple EAs and the EGS they provide. However, the structure was deliberately simplistic because there is a growing realisation that approaches capturing higher-level complexity can lead to a false sense of confidence in model quality (Bagstad et al., 2013).

For any communication tool to be effective, they must provide information that is relevant and accessible to stakeholders. In developing countries, engaging community stakeholders in the learning process builds their adaptive capacity through empowerment (Butler et al., 2015). More broadly, for expert-driven models to effectively communicate science, tools must be transparent, quantifiable, replicable, relevant, credible, affordable and unbiased (Cash et al., 2003; Bagstad et al., 2013). Also, they must be flexible enough to include new knowledge or updated climate projections within iterative decision-making processes (Webster et al., 2003; Wise et al., 2014).

When subjectively assessed against Cash et al.'s (2003) criteria for effective communication of scientific data and Bagstad et al.'s (2013) attributes of ecosystem service assessments, ADWIM performed well (Table 2). In particular, ADWIM's attributes of transparency, credibility, flexibility, affordability and providing unbiased information promotes its utility and usefulness. It was also highly relevant to stakeholders because of the EGS considered, namely the goods and services which are

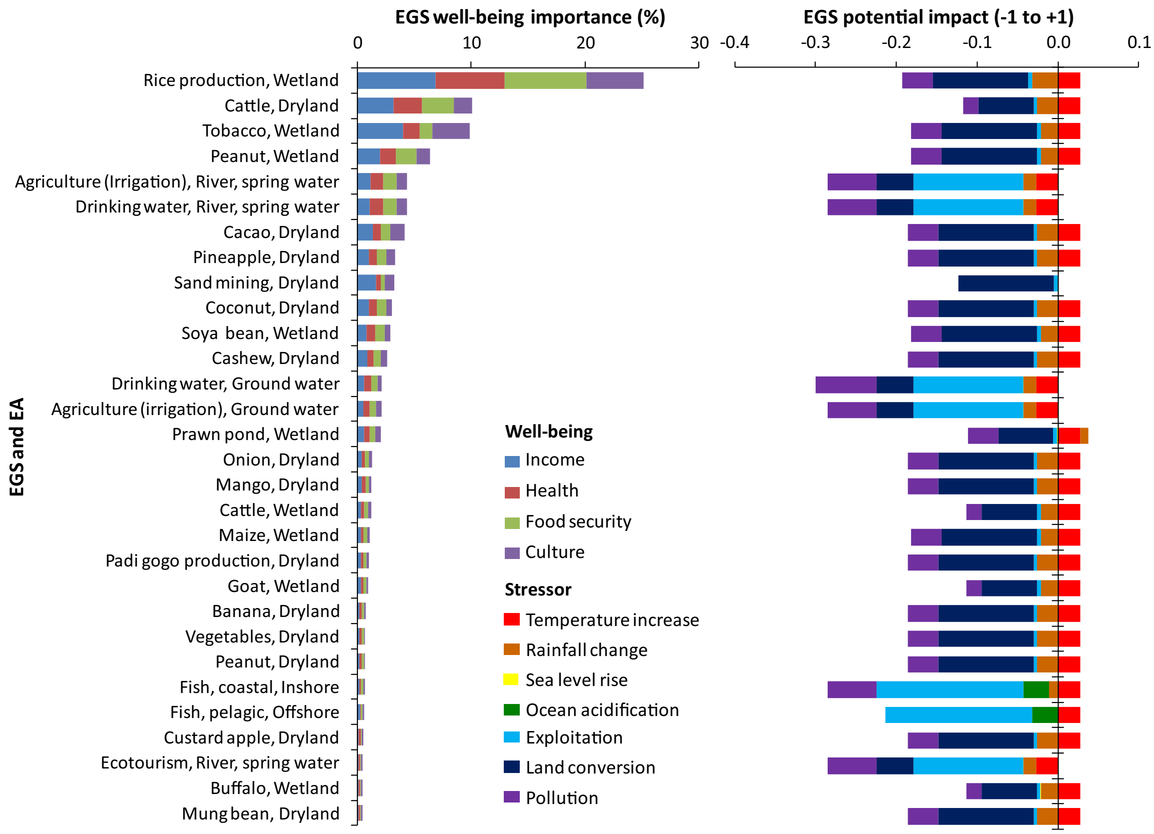

Fig. 4. Ecosystem goods and services (EGS) and their supporting ecosystem asset (EA) in Type 5 of the provincial subdistrict typology, showing their well-being importance in terms of income, health, food security and culture (left). Potential impacts in 2030 (right) are shown for each EGS in terms of stressors from climate change and population growth. Only the 30 most important EGS are listed.

Subdistrict type	Total well-being impact (%)		
	2030	2060	2090
Type 7	-11.8	-15.5	-25.4
Type 3	-11.6	-14.4	-26.6
Type 4	-9.5	-10.9	-22.2
Type 5	-8.9	-11.7	-23.9
Type 1	-6.2	-9.2	-19.4
Type 6	-6.1	-6.4	-12.6
Type 2	-5.6	-6.0	-15.9

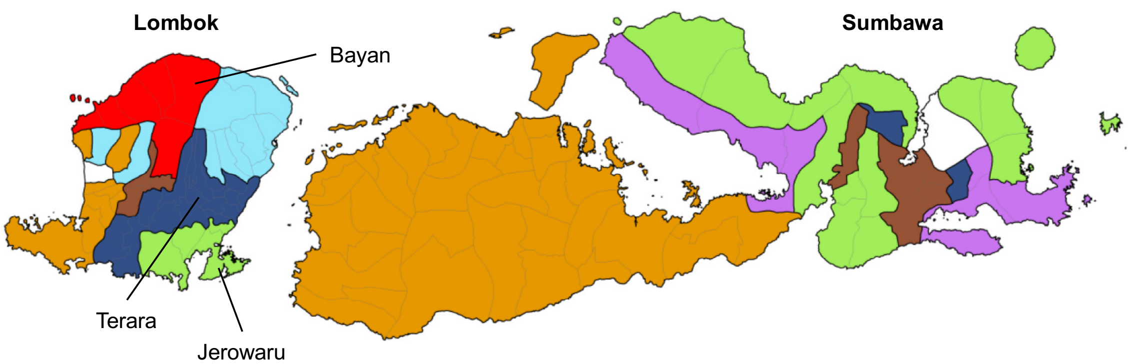

Fig. 5. Total well-being impact for the seven subdistrict types in NTB (see Rochester et al. (2016) for further details). Urban municipalities are coloured white. Locations of Jerowaru, Terara and Bayan case study subdistricts are also shown.

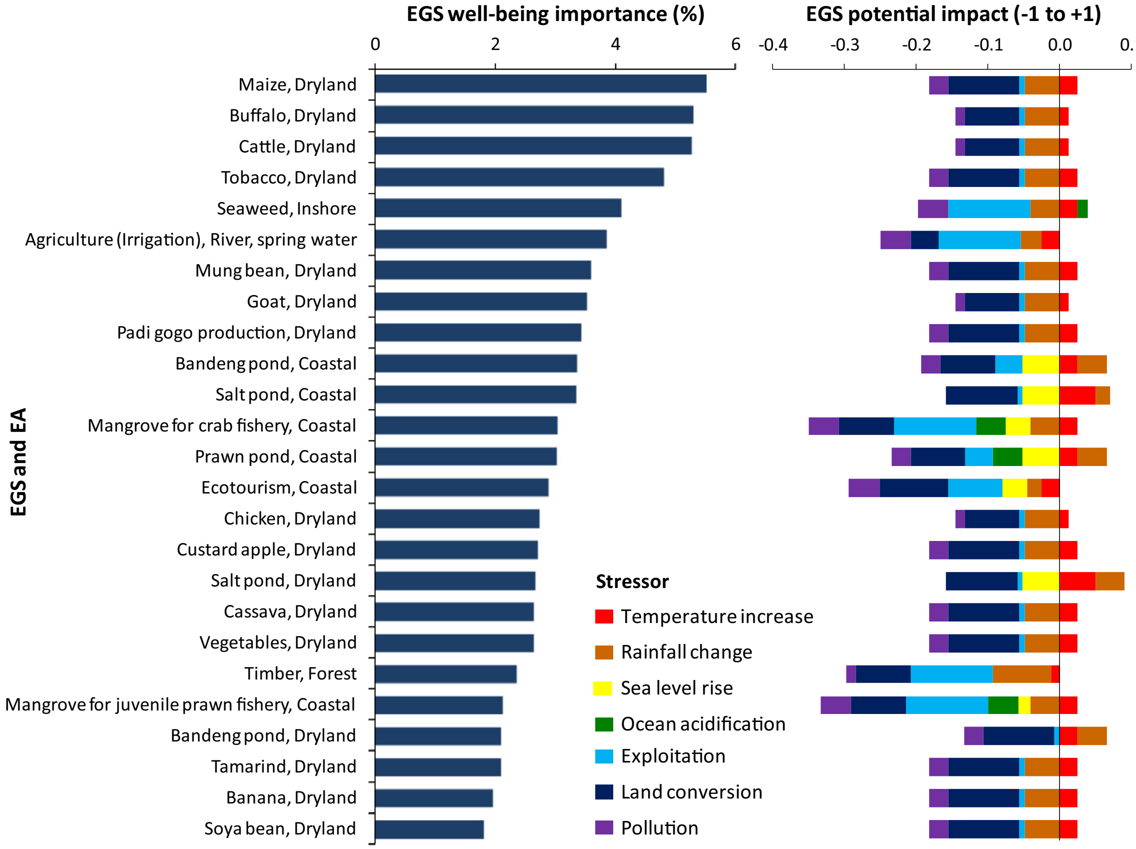

Fig. 6. Ecosystem goods and services (EGS) and their supporting ecosystem asset (EA) in Jerowaru subdistrict, showing their well-being importance (left). Note that for illustration this has not been disaggregated into income, health, food security and culture. Potential impacts in 2030 (right) are shown for each EGS in terms of stressors from climate change and population growth. Only the 25 most important EGS are listed.

actually and directly valued and consumed by people (Wallace, 2007; Kent and Dorward, 2012). In NTB many rural households include multiple off-farm activities in their livelihood portfolios such as employment in government, small businesses and as labourers (Lisson et al., 2010; Butler et al., 2014a). Nonetheless, it was assumed that ecosystem-based activities were of primary importance. To test this we conducted a questionnaire survey of participants at scenario planning workshops for Jerowaru and Terara subdistricts, plus a third case study, Bayan (see Fig. 5). Results indicated that relative to external employment or other sources of income, EGS directly contributed 57% and 56% of community well-being in Jerowaru and Terara, respectively, and 67% in Bayan (Fig. 8).

However, the reasons for this relevance also exposed one of ADWIM's limitations. While EAs were considered to provide stocks of EGS, the role of other services was ignored, such as 'regulating' (benefits obtained from the regulation of ecosystem processes) and 'supporting' services (those necessary for the production of all other ecosystem services; Millennium Ecosystem Assessment, 2005). Also, the central role of biodiversity in ecological processes was ignored. These landscape-scale services can also provide ecosystem-based adaptation benefits (e.g. Jones et al., 2012) or 'adaptation services' (Lavorel et al., 2014), for example, by controlling coastal erosion or maintaining ecological connectivity. While these benefits may not be recognised by communities, and therefore could be regarded as irrelevant, their contribution to adaptation and adaptation strategies is important. Similarly, the role of biodiversity may be overlooked by communities, but certain species' intrinsic values are of importance to off-site stakeholders (Rodriguez et al., 2006; Butler et al., 2013).

The simplistic nature of ADWIM also necessitated seven major assumptions which influenced the outputs (Table 3). Three of these have important ramifications because they potentially underestimate the negative impacts climate change and population growth will have on EGS and therefore community well-being. First, climate-driven stressors were averaged over 20 years for each time slice therefore did not account for extreme events. However, under the 'Business as Usual' global emissions scenario extreme events such as droughts and floods are likely to increase in frequency and intensity in eastern Indonesia (Kirono et al., 2016), and hence impacts on EGS could be severe in some years. Second, the assumption of additive impacts ignores potential synergistic and antagonistic system effects, which are recognised in many ecosystems (e.g. Crain et al., 2008; Griffith et al., 2012). Third, the assumed linear relationship between EA condition and the flow of EGS overlooks the possibility that there may be thresholds in EA condition that triggers a sudden decline in EGS flows. For example, when

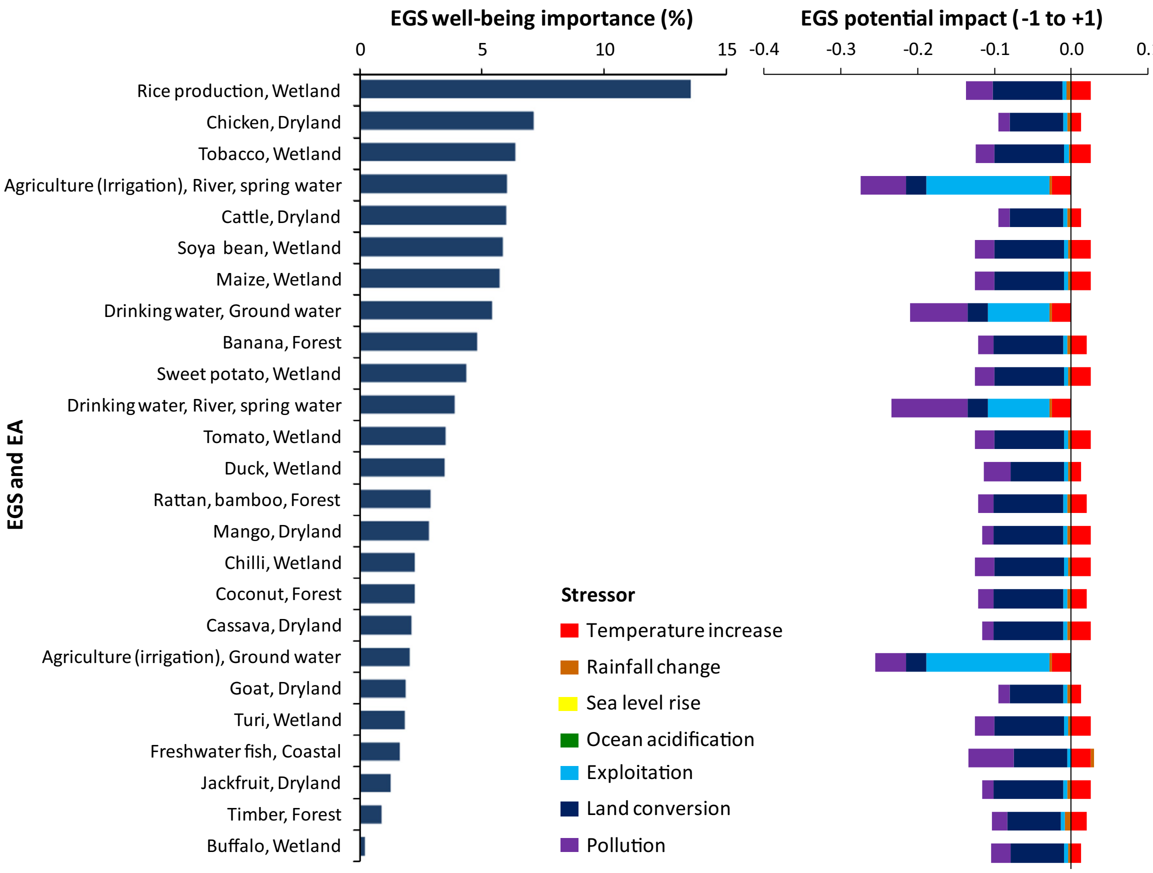

Fig. 7. Ecosystem goods and services (EGS) and their supporting ecosystem asset (EA) in Terara subdistrict, showing their well-being importance (left). Note that for illustration this has not been disaggregated into income, health, food security and culture. Potential impacts in 2030 (right) are shown for each EGS in terms of stressors from climate change and population growth. Only the 25 most important EGS are listed.

catch per unit effort for a fish stock becomes too low to justify the cost of harvesting, the EGS flow halts despite some fish still being available to catch.

Two other factors may exacerbate the tendency of ADWIM to underestimate impacts. First, the climate change data were derived from CCAM modelling, which applied the SRES A2 global emissions scenario (IPCC, 2007; McGregor et al., 2016). At the time of the study, this was considered to be one of the 'Business as Usual' scenarios. However, actual emissions in 2007-2012 have generally been higher than SRES A2 and therefore are likely to result in more acute climate change (IEA, 2014). Second, the population growth projections were based on the United Nation's median variant method, and did not apply potentially higher growth rates.

There are three aspects of ADWIM which could be refined, potentially enhancing its attributes of transparency and relevance. First, ADWIM does not currently present metrics for uncertainties or confidence intervals in any of the outputs. While these are included in the narratives of EAs' sensitivity to changes in stressors, the implications are not propagated through the matrices. One option would be to invite the experts canvassed in Step 1 to provide confidence intervals on a simple semi-quantitative scale, which could be illustrated in the EGS potential impact graphs. However, there may be a trade-off between adding greater transparency to the outputs, and reducing their relevance by generating more conceptual and visual complexity.

Second, thresholds could be determined in the relationship between EA condition and EGS flow. Currently it is assumed that there is a proportional relationship, but this is unlikely to be true, and thresholds may induce ecosystem shifts which will radically affect EGS flows. Third, EGS derived from outside the unit of analysis should be incorporated, and the potentially different impacts of climate- and population-driven stressors. This limitation is of greatest relevance for finer scales of analysis, where communities may derive benefits from EAs in neighbouring subdistricts and villages. Also, coastal fishing communities in NTB may travel large distances (50–100 km) to access fish stocks (Karnan et al., 2011), particularly in some Type 1 subdistricts where the off-shore pelagic EGS was important.

Table 2
A subjective assessment of ADWIM's attributes relative to the eight criteria for effective communication of scientific data (from Cash et al., 2003) and ecosystem service assessments (from Bagstad et al., 2013).

Criteria	Self-assessment
1. Transparent	Information on drivers and stressors presented during preliminary sessions of planning workshops discussing drivers of change
	Sensitivity and exposure narratives include referenced sources, and can be reviewed by peers and other experts
	Initial EGS inventory identified by experts and literature, but verified and refined by workshop participants
	EGS well-being importance, potential and total well-being impacts calculated in real-time during workshops
2. Quantifiable	Semi-quantified scoring of EGS values, potential and total well-being impacts
3. Replicable	Excel spreadsheet format easily replicated
	Explicit assumptions
	Low model complexity enabling real-time adjustment to updated information on drivers, stressors and EGS values
4. Relevant	Analyses EGS directly valued and consumed by local communities
	Communities are largely dependent on EGS
	Analysis and outputs of direct relevance to the unit of analysis and its stakeholders
	Outputs targeted at the formulation of adaptation strategies
5. Credible	EGS well-being importance defined by participants through valuation process in workshops
	Information on drivers and stressors presented in local language (i.e. Bahasa Indonesia)
	Outputs labelled and explained in local language (i.e. Bahasa Indonesia)
6. Flexible	Applicable at multiple levels (e.g. province, subdistrict, village)
	Can incorporate multiple forms of knowledge (e.g. secondary data, expert opinion, scientific literature)
7. Affordable	Low model complexity requires minimal time for preparation
	Expert elicitation can be undertaken individually or collectively (e.g. workshop)
	Once established, Step 1 cumulative impact spreadsheets are transferable to other units of analysis
8. Unbiased	Initial EGS inventory identified by experts and from literature, but verified and refined by workshop participants
	EGS well-being importance defined by participants through valuation process in workshops
	Where available, driver and stressor data sourced from secondary data (e.g. (population census) or scientific literature (e.g. CCAM downscaled climate projections)

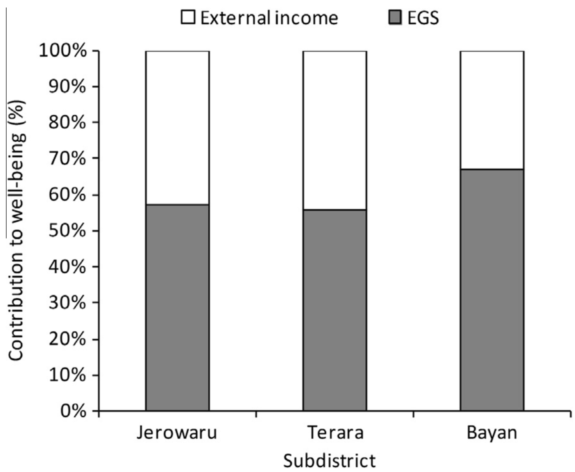

Fig. 8. The contribution to community well-being derived directly from EGS relative to external income in Jerowaru (n = 17), Terara (n = 17) and Bayan (n = 20) subdistricts (see Fig. 5). Questionnaires asked participants to score on a scale from 0 (none) to 5 (very important) the relative contribution made to food security, health and culture by EGS and external income. Data were aggregated and standardised to 100%. Sample sizes of respondents are shown.

Conclusions

We have presented a simple and robust participatory decision-support tool designed for adaptation planning processes in developing countries, where secondary data sources are patchy, and the communication of scientific information must be particularly relevant, transparent and credible. ADWIM is novel because it not only accounts for multiple stressors on multiple EGS, but it also bridges the conceptual boundary between ecosystem services modelling and adaptation planning. Based on our experiences of applying the tool in NTB, we found that its attributes meet many of the criteria required for the effective communication of science to multiple stakeholders. The method also proved to be useful to participants to focus adaptation actions on high priority impacts to important EGS.

While ADWIM provides many advantages in these respects, the trade-off is the assumptions which potentially underestimate the impacts of climate change and population growth on EGS and well-being. ADWIM's relevance is in large part due

Table 3
Assumptions made in ADWIM, and their potential implications for results.

Assumption	Implications for results
Constant management and utilisation patterns	Over time communities and other stakeholders may alter management practices and substitute current EGS with new EGS (e.g. alternative crops), or other external employment. Therefore long term analyses are less credible. To mitigate this, the 2030 time horizon was emphasized because the current portfolio of EGS is unlikely to alter significantly
Constant values of EGS	Limits the credibility of long term analyses. To mitigate this, the 2030 time horizon was emphasized because the current volumes and values of EGS are unlikely to alter significantly
EGS only derived within unit of analysis	Underestimates the contribution of EGS from outside the unit of analysis, and the differing effect of drivers and stressors on these EGS. This error is more likely to occur at finer scales of analysis (i.e. subdistricts and villages)
Averaged climate stressors	Climate-driven extremes in stressors (e.g. drought, flood) may have a greater impact on the exposure of EAs, underestimating impacts on EGS
Additive impacts on EGS	Underestimates potential impacts from feedback loops and non-linear system effects on EAs and EGS
Linear relationships between EA status and EGS flows	Ignores potential non-linear relationships between the condition of EAs and EGS flows, underestimating impacts on EGS
Linear relationship between population density and land conversion	Ignores the possibility that housing density could be reduced by multi-story buildings, overestimating the impact of population growth on land conversion, EAs and EGS flows

to its focus on EGS which are directly valued and used by rural communities, but this overlooks underlying ecosystem services and biodiversity. The likelihood that the portfolio of EGS will alter in the long term, and their values will change as economic and social development occurs (Stage, 2010), necessitates a focus on the near term impacts. However, while the nature of EGS' contributions to well-being and livelihoods may shift from a primarily provisioning to cultural function (Rodriguez et al., 2006), EGS are likely to remain a critical direct or indirect facet of well-being, particularly for poorer households (Millennium Ecosystem Assessment, 2005). Consequently, in spite of its limitations, ADWIM provided a useful and flexible 'boundary object' with which to stimulate discussion and integrate knowledge amongst multiple stakeholders with differing world-views and perceptions (Star and Griesemer, 1989; Wenger, 1998; White et al., 2010).

Acknowledgements

We acknowledge funding support from the Australian Government's Department of Foreign Affairs and Trade-CSIRO Research for Development Alliance. We also thank the workshop participants in NTB who contributed to the testing of ADWIM. Brian Long, Wayne Rochester and Ian McLeod (CSIRO Oceans and Atmosphere Flagship) contributed secondary data sourcing and processing for the workshops. David Brewer and Leo Dutra provided useful comments that improved the manuscript.

References

Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst. Serv. 5, 27–39.

Butler, J.R.A., Wong, G., Metcalfe, D., Honzak, M., Pert, P.L., Bruce, C., Kroon, F.J., Brodie, J., 2013. An analysis of trade-offs between multiple ecosystem services and stakeholders linked to land use and water quality management in the Great Barrier Reef, Australia. Agric. Ecosyst. Environ. 180, 176–191.

Butler, J.R.A., Suadnya, W., Puspadi, K., Sutaryono, Y., Wise, R.M., Skewes, T.D., et al, 2014a. Framing the application of adaptation pathways for rural livelihoods and global change in Eastern Indonesian islands. Global Environ. Change 28, 368–382.

Butler, J.R.A., Skewes, T., Mitchell, D., Pontio, M., Hills, T., 2014b. Declining ecosystem service trajectories in Milne Bay, Papua New Guinea: is human population pressure a more critical driver than climate change? Marine Policy 46, 1–13.

Butler, J.R.A., Wise, R.M., Skewes, T.D., Bohensky, E.L., Peterson, N., Suadnya, W., Yanuartati, Y., Handayani, T., Habibi, P., Puspadi, K., Bou, N., Vaghelo, D., Rochester, W., 2015. Integrating top-down and bottom-up adaptation planning to build adaptive capacity: a structured learning approach. Coastal Manag. 43, 346–364.

Butler, J.R.A., Kirono, D., Bohensky, E.L., Wise, R.M., Darbas, T., Sutaryono, Y., 2016. Building capacity for adaptation pathways in eastern Indonesian islands: synthesis and lessons learned. Clim. Risk Manage. 12, A1–A10.

Butler, J.R.A., Suadnya, I.W., Yanuartati, Y., Meharg, S., Wise, R.M., Sutaryono, Y., Duggan, K., 2016. Designing and evaluating the priming of adaptation pathways in developing countries. Climate Risk Manag. Clim. Risk Manage. 12, 1–16.

Butler, J.R.A., Bohensky, E.L., Suadnya, W., Yanuartati, Y., Handayani, T. Habibi, P., Puspadi, K., Skewes, T.D., Wise, R.M., Suharto, I. Park, S.E., Sutaryono, Y., 2016. Scenario planning to leap-frog the Sustainable Development Goals: an adaptation pathways approach. Clim. Risk Manage. 12, 83–99.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. U.S.A. 100 (14), 8086–8091. http://dx.doi.org/10.1073/pnas.1231332100.

Cash, D.W., Borck, J.C., Patt, A.G., 2006. Countering the loading-dock approach to linking science and decision making – comparative analysis of El Nino/Southern Oscillation (ENSO) forecasting systems. Sci. Technol. Human Values 31 (4), 465–494. http://dx.doi.org/10.1177/0162243906287547.

Chin, A., Kyne, P.M., Walker, T.I., McAuley, R.B., 2010. An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. Glob. Change Biol. 16 (7), 1936–1953. http://dx.doi.org/10.1111/j.1365-2486.2009.02128.x.

Crain, C.M., Kroeker, K., Halpern, B.S., 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecol. Lett. 11, 1304–1315.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7 (1), 21–28. http://dx.doi.org/10.1890/080025.

Dorward, A.R., 2014. Livelisystems: a conceptual framework integrating social, ecosystem, development, and evolutionary theory. Ecol. Soc. 19 (2), 44.

Ensor, J., 2011. Uncertain futures: adapting development to a changing climate. Practical Action Publishing, Rugby, UK.

Fachry, A., Hanartani, Supartiningsih, S. Butler, J.R.A., 2011. Social, cultural and economic trends in NTB and their drivers of change. AusAID–CSIRO Research for Development Alliance, University of Mataram, NTB Government. CSIRO Climate Adaptation Flagship, Brisbane, and University of Mataram, Lombok. Available at: http://ccap-unram.org/.

Farr, T.G. et al, 2007. The shuttle radar topography mission. Rev. Geophys. 45, RG2004. http://dx.doi.org/10.1029/2005RG000183.

Gidley, J.M., Fien, J., Smith, J.A., Thomsen, D.C., Smith, T.F., 2009. Participatory futures methods: towards adaptability and resilience in climate vulnerable communities. Environ. Policy Govern. 19, 427–440.

Griffith, G.P., Fulton, E.A., Gorton, R., Richardson, A.J., 2012. Predicting interactions among fishing, ocean warming, and ocean acidification in a marine system with whole-ecosystem models. Conserv. Biol. 26, 1145–1152.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Williams, S.L., 2006. The impacts of climate change in coastal marine systems. Ecol. Lett. 9 (2), 228–241. http://dx.doi.org/10.1111/j.1461-0248.2005.00871.x.

I.E.A., 2014. CO_2 Emissions from Fuel Combustion (2014 Edition). I.E.A., Paris.

Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. Harnessing nature to help people adapt to climate change. Nat. Clim. Change 2, 504–509.

Karnan, Junaida, M., Cokrowati, N., 2011. Sumbawa Marine Resources Survey. AusAID-CSIRO Research for Development Alliance, University of Mataram, NTB Government. University of Mataram, Lombok. Available at: http://ccap-unram.org/.

Kent, R., Dorward, A., 2012. Conceptualizing assets and asset services in livelihoods and ecosystem analyses for poverty reduction. Working Paper, Centre for Development, Environment and Policy, SOAS, University of London.

Kirono, D.G.C., McGregor, J., Butler, J.R.A., Ripaldi, A., Katzfey, J., Nguyen, K., 2016. Historical and future seasonal rainfall variability in Nusa Tenggara Barat Province, Indonesia: implications for the agriculture and water sectors. Clim. Risk Manage. 12, 45–58.

Lavorel, S., Collof, M., McIntyre, S., Doherty, M., Murphy, H.T., Metcalfe, D.J., Dunlop, M., Williams, R.J., Wise, R.M., Williams, K.J., 2014. Ecological mechanisms underpinning climate adaptation services. Glob. Change Biol. http://dx.doi.org/10.1111/gcb.12689.

Lisson, S., MacLeod, N., McDonald, C., Corfield, J., Pengelly, B., Wirajaswadi, L., Rahman, R., Bahar, S., Padjung, R., Razak, N., Puspadi, K., Dahlanuddin, Sutaryono, Y., Saenong, S., Panjaitan, T., Hadiawati, L., Ash, A., Brennan, L., 2010. A participatory farming systems approach to improving Bali cattle production in the smallholder crop-livestock systems of Eastern Indonesia. Agric. Syst. 103, 486–497.

McGregor, J.L., Nguyen, K.C., Kirono, D., Katzfey J., 2016. Downscaling climate projections for the islands of Lombok and Sumbawa, Nusa Tenggara Barat Province, Indonesia: challenges and applications. Clim. Risk Manage. 12, 32–44.

Millennium Ecosystem Assessment, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: a Framework for Assessment. Island Press, Washington DC.

Ministry of Environment, MoE, 2010. Risk and Adaptation Assessment to Climate Change in Lombok Island. Synthesis Report. Ministry of Environment, Indonesia, West Nusa Tenggara Province, p. 97.

Nelson, R., Kokic, P., Crimp, S., Meinke, H., Howden, S.M., 2010. The vulnerability of Australian rural communities to climate variability and change: Part I – conceptualising and measuring vulnerability. Environ. Sci. Policy 13, 8–17.

Plagányi, É.E., Bell, J.D., Bustamante, R.H., Dambacher, J.M., Dennis, D.M., Dichmont, et al, 2011. Modelling climate change effects on Australian and Pacific aquatic ecosystems: a review of analytical tools and management implications. Marine Freshwater Res. 62, 1132–1147.

Reed, M.S., Podesta, G., Fazey, I., Geeson, N., Hessel, R., Hubacek, K., et al, 2013. Combining analytical frameworks to assess livelihood vulnerability to climate change and analyse adaptation options. Ecol. Econ. 94, 66–77. http://dx.doi.org/10.1016/j.ecolecon.2013.07.007.

Rochester, W.A., Skewes, T.D., Suadnya, W., Butler, J.R.A., Lyne, V.D., Handayani, T., et al., 2016. A typology of natural resource use for livelihood impact assessments in Nusa Tenggara Barat Province, Indonesia. Clim. Risk Manage. 12, 59–68.

Rodriguez, J.P., Beard, T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., et al, 2006. Trade-offs across space, time, and ecosystem services. Ecol. Soc. 11 (1), 28.

Stage, J., 2010. Economic valuation of climate change adaptation in developing countries. Ann. N. Y. Acad. Sci. 1185, 150–163.

Star, S.L., Griesemer, J.R., 1989. Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. Soc. Stud. Sci. 19 (3), 387–420.

United Nations, 2002. World Population Prospects The 2000 Revision Volume III: Analytical Report. United Nations, New York.

United Nations, 2014. We can end poverty. Millennium development goals and beyond 2015. United Nations, New York. http://www.un.org/millenniumgoals/poverty.shtml.

Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Portela, R., Honzak, M., Batker, D., 2014. A methodology for adaptable and robust ecosystem services assessment. PLoS ONE 9 (3). http://dx.doi.org/10.1371/journal.pone.0091001.

Wallace, K.J., 2007. Classification of ecosystem services: problems and solutions. Biol. Conserv. 139, 235–246.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., et al, 2003. Uncertainty analysis of climate change and policy response. Clim. Change 61 (3), 295–320. http://dx.doi.org/10.1023/B:CLIM.0000004564.09961.9f.

Wenger, E., 1998. Communities of Practice: Learning, Meaning, and Identity. Cambridge University Press, Cambridge, ISBN 978-0-521-66363-2.

White, D.D., Wutich, A., Larson, K.L., Gober, P., Lant, T., Senneville, C., 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. Sci. Public Policy 37, 219–232.

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer van Garderen, E.R.M., Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Glob. Environ. Change 28, 325–336. http://dx.doi.org/10.1016/j.gloenvcha.2013.12.002.

Wise, R.M., Butler, J.R.A., Suadnya, W., Puspadi, K., Suharto, I., Skewes, T.D., 2016. How climate compatible are livelihood adaptation strategies and development programs in rural in Indonesia? Clim. Risk Manage. 12, 100–114.

Yasin, I., Ma'shum, M., Idris, H., Abawi, Y., 2007. The impact of inter-annual climate variability on water resource and crop production in Lombok. In: Klock, J., Sjah, T. (Eds.), Water Management in Lombok, Indonesia: Challenges and Solutions. Mataram University Press, Lombok, Indonesia, pp. 53–87.