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Seaweed farming collapse and fast changing socio-ecosystems exacerbated by tourism and natural hazards in Indonesia: A view from space and from the households of Nusa Lembongan island.

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ABSTRACT

The culture of seaweed for the food and cosmetics industry is central to many rural households in Indonesia. The activity has vastly expanded in the past three decades, but in some cases, an opposite trend is now emerging. Spaceborne images were used to monitor the recent collapse of seaweed farming around the small island of Nusa Lembongan, Bali, Indonesia. A simple semi-quantitative Seaweed Farming Index highlighted the different dynamics for four different sectors around the island, with abrupt or gradual changes starting in 2012. By 2017, seaweed farming had eventually vanished from the island, after sustaining local livelihoods for more than 30 years and influencing the zoning plan of the local Marine Conservation Area since 2010. Interviews of 50 ex-farmers in 2018 identified the reasons of the changes: failed crop, low selling prices, shrinking space to dry algae against coastal development, and easy alternative jobs in tourism, although not necessarily providing better salary incomes. Tourism attracted half of these farmers, while another 25% went into building construction, itself largely driven by tourism development. The vulnerability of a complete shift to tourism was highlighted when tourism temporarily collapsed for several months due to threat of a Bali volcano eruption in late 2017. This prompted ex-farmers to consider returning to farming. This integrated case study based on remote sensing and household surveys highlights the fast-changing dynamics of Indonesia coastal socio-ecosystem due to largely to tourism development and natural hazards. The consequences for local management are discussed.

1. Introduction

Social and economic changes in tropical countries are happening at a fast pace, due to climate change, natural hazards, policy, globalization, enhanced transports and access to information, and better education. These changes happen even for the most remote places and smallest islands (Ferro-Azcona et al., 2019). Whether they are developing or declining, resource extraction (fisheries), aquaculture and tourism are globally important drivers of tropical coastal livelihoods changes (Cinner, 2014; Spalding et al., 2017; Oyinlola et al., 2018). In Indonesia, there is a growing interest in how tourism, coral reef conditions and seaweed farming influence the socio-ecosystem of an island in or outside marine protected areas (Hurtado et al., 2014; Kurniawan et al., 2016a, 2016b; Hidayah et al., 2016; Steenbergen et al., 2017). However, why and how livelihoods have changed recently at the scale of a community remains understudied (Steenbergen et al., 2017). In particular, despite Indonesia being exposed to many geophysics risks (earthquake, tsunami, volcanic eruption) (Meltzner et al., 2006; Hidayah et al., 2016; Ferro-Azcona et al., 2019), the role of natural hazards in shaping present small island socio-ecosystems has been little studied (Kelman, 2017). The size of Indonesia, the number and the scattering of islands (~16,000 following Martha 2017) make this type of assessment difficult. In this archipelagic geographic context, very few remote sensing studies have successfully mapped changes to identify indicators of socio-ecosystems changes (Kurniawan et al., 2016b; Gusmawati et al., 2018). The potential of remote sensing to detect early the changes affecting Indonesian islands is probably under-used. We focus here on these issues with a case study on Nusa Lembongan Island.

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Nusa Lembongan is an island of the Klungkung regency in Bali. With its Nusa Ceningan and Nusa Penida neighbors, it is located 12 km offshore from the main tourist hub of south Bali (Fig. 1). Nusa Lembongan was since the 1980s a laid back area for tourists (Long and Wall, 1996). Tourism development however surged in the 2000s bringing new activities and type of clients, up-scaled hotels, more family homestays and transport activities. The development took advantage of the fleet of fast boats from Sanur inBali to transport tourists (Fig. 1).

Tourism has not always been the main activity. Since the late 1970s, seaweed farming of *Kappaphycus alvarezii* (previously *Euchema cottonii*) and *Eucheuma denticulatum* (previously *E. spinosum*) was intensive year-long along the shores of the three islands (Carter et al., 2014; Hurtado et al., 2014). This activity is widespread in Indonesia and Southeast Asia (Blankenhorn, 2007; Hurtado et al., 2014; Buschmann et al., 2017; Waters et al., 2019). In Nusa Lembongan, the farming recently became an attraction itself since tourists could visit farmers and witness their activities. The activity was so rooted in the community that within the 20.000 ha of the Nusa Penida Marine Conservation Area (also called KKP-*Kawasan Konservasi Perairan*) implemented in 2010, large sections of reef flat and lagoon areas were reserved for seaweed farming (Carter et al., 2014).

During a habitat mapping survey in November 2015 (by IRD and IMRO), extensive seaweed farming was still occurring and was visible on the very high resolution 2015 WorldView2 satellite image used for the mapping. However, in August 2016 and February 2017, during subsequent IRD-IMRO surveys, the level of activity had decreased and eventually disappeared. This prompted the question of whether or not the 2017 situation was the result of a lasting trend and what could have motivated it?, or was it just a short hiccup in farming production? The decision was taken in mid-2017 to try to monitor this trend.

In late November 2017, a new episode on the socio-economic dynamics of Nusa Lembongan was triggered by an eruption of Mount Agung, the main Bali volcano (Marchese et al., 2018; Syahbana et al., 2019). The airport closed due to clouds of ashes, stopping overnight the influx of tourist and prompting the cancellation of tens of thousands of reservations made for the December–January holiday season, resulting in an average drop of 20–30% of the usual hotel occupancy rates, and up to 50–80% in some cases (Rahmawati et al., 2019). During almost three months, the Bali tourism industry struggled, with fear that the Mount Agung crisis would last more permanently.

The fast-changing socio-economic evolution of the island prompted a combined remote sensing and *in situ* assessment based on very high resolution satellite images and household surveys respectively. Both types of information were used to 1) confirm the trends of changing activity visible on satellite imagery, 2) assess why farmers quit their activity, and 3) discuss what are the likely possible future options and the consequences for the management of the island. Beyond Nusa Lembongan, and considering the extent of Indonesia and the often limited technical capacities in many islands, we favored simple and low cost remote sensing approaches that should promote more easily capacity building and generalization to other case studies (Andréfouët 2008).

2. Material and methods

2.1. Ethical statement

Ethical review and written consent was not required for this study with human participants in accordance with the local Indonesian legislation and institutional requirements. All informants were provided the content and goals of the study, and approved the use of their information, pending personal information (names) will not be used and kept confidential. Approval was confirmed before and after the interviews.

2.2. Study site

The Nusa Lembongan island consists of 2 villages (Lembongan and Jungutbatu) and 12 sub-villages (in Bali, called *banjar dinas*). The terrestrial and mangrove area covers 9.14 km^2, while the reef flats and slopes around the island cover 7.54 km^2. The local population reaches about 4400 inhabitants. In September 2019, the official numbers reported 398 homestays, hotels, resorts and villas, all offering lodging and tourism services in Nusa Lembongan and Nusa Ceningan. This number corresponded to information seen on Google Map® in September 2019, where 330 addresses were visible on the 6.15 km^2 of Nusa Lembongan land. This corresponds to a density of 53.6 touristic lodging structures per km^2.

Fig. 1. Location map of Nusa Lembongan relative to Bali, and the Gunung Agung volcano.

Before 2012, seaweed farming took place almost all around the island. Space for the activity was legally reserved around the three islands in the Marine Conservation Area. The reserved seaweed farming area covered mostly the wide sedimentary area but also the hard-bottom coral reef flats. Farming took place in very shallow waters, approximately less than 1.2 m at high tide. Four different sectors were considered for this study (Fig. 2). First, the largest sector was exposed to the northwest, facing Bali. The main island village, Jungutbatu, borders this sector. Second, the north sector was a much narrower sedimentary and reef flat area, protected from the high energy waves. Third, the northeast sector was also a protected narrow band of sediment and reef flat, sandwiched between a mangrove and the channel separating Nusa Lembongan from Nusa Penida, where strong current prevails. Fourth, in the south, a large sheltered sedimentary area between Nusa Lembongan and Nusa Ceningan was exploited by villagers from both islands (Fig. 2). The seaweed farming area extended southward almost until the reef crest which protects the site from incoming Indian Ocean swells.

2.3. Satellite imagery and processing for seaweed farming detection

Very high spatial resolution (VHR, 2 m) satellite images were used to monitor changes in seaweed farming extent. The INDESO project (Andréfouët et al., 2018) provided three images of Nusa Lembongan, acquired in 2013 (WorldView2 sensor 19th March, 17th October) and 2014 (GeoEye-1 sensor 11th October). Other days could be investigated at no cost using MAXAR (previously DigitalGlobe) imagery visible on Google Earth ® (GE). A number of cloud free images were available from May 2003 till July 2019, although not all sectors were covered the exact same days (Table 1). MAXAR image quality was variable, some presenting breaking waves zones along the reef crest of the south and northwest sectors. For each sector, changes were thus quantified on domains that were always clear in all available images.

Seaweed farming in Nusa Lembongan is an inherently dynamic process. Farmed plots are frequently harvested, after few weeks to couple of months of growth (Waters et al., 2019). The farmed areas are generally divided in sharply defined rectangular-shaped plots (Fig. 2). Each rectangle, which is often materialized by a short fence made of wood, vegetation and nets, is exploited by a different owner, and some plots can be farmed while others nearby can be left unproductive. Also, at low density, and at the beginning of the farming process, farmed biomass is low and the plot can look unfarmed. Plots left too long without maintenance see the materials that form the plot border rapidly degrade. Plots become less visible on images as their physical limit slowly disappear. The decrease of activity was visually obvious on the images after 2015, with the dark patches of farmed plots turning into optically bright areas representative of sandy areas (Hochberg et al., 2003) (Fig. 2). Considering the strong optical contrast between a dark farmed plot and sand, and considering that our objectives were only to confirm the trend of decreasing activity across time, a semi-quantitative approach was deemed adequate to detect changes in the different sectors. Furthermore, considering the GE origin of the images, no atmospheric correction or water column correction was analytically possible.

Table 1
Date (DD/MM/YY) of images available for each sector.

Sector			
Northwest	North	Northeast	South
29/05/2003	29/05/2003	29/05/2003	29/05/2003
06/08/2005	06/08/2005	15/10/2009	15/10/2009
15/10/2009	15/10/2009	12/12/2009	12/12/2009
12/12/2009	12/12/2009	15/09/2012	15/09/2012
15/09/2012	15/09/2012	11/10/2012	11/10/2012
11/10/2012	11/10/2012	19/03/2013	19/03/2013
19/03/2013	19/03/2013	17/10/2013	17/10/2013
11/09/2013	17/10/2013	11/10/2014	11/10/2014
17/10/2013	11/10/2014	06/02/2015	03/11/2014
11/10/2014	03/11/2014	02/03/2015	21/12/2014
03/11/2014	21/12/2014	07/11/2015	06/02/2015
21/12/2014	06/02/2015	02/05/2016	14/07/2015
06/02/2015	02/03/2015	16/05/2017	07/11/2015
02/03/2015	07/11/2015	09/06/2017	16/05/2017
07/11/2015	02/05/2016	16/08/2017	16/08/2017
09/06/2017	09/06/2017	04/11/2017	30/01/2018
16/08/2017	16/08/2017	30/01/2018	06/04/2018
30/01/2018	30/01/2018	20/07/2018	20/07/2018
20/07/2018	20/07/2018	18/10/2018	18/10/2018
18/10/2018	18/10/2018	31/07/2019	31/07/2019

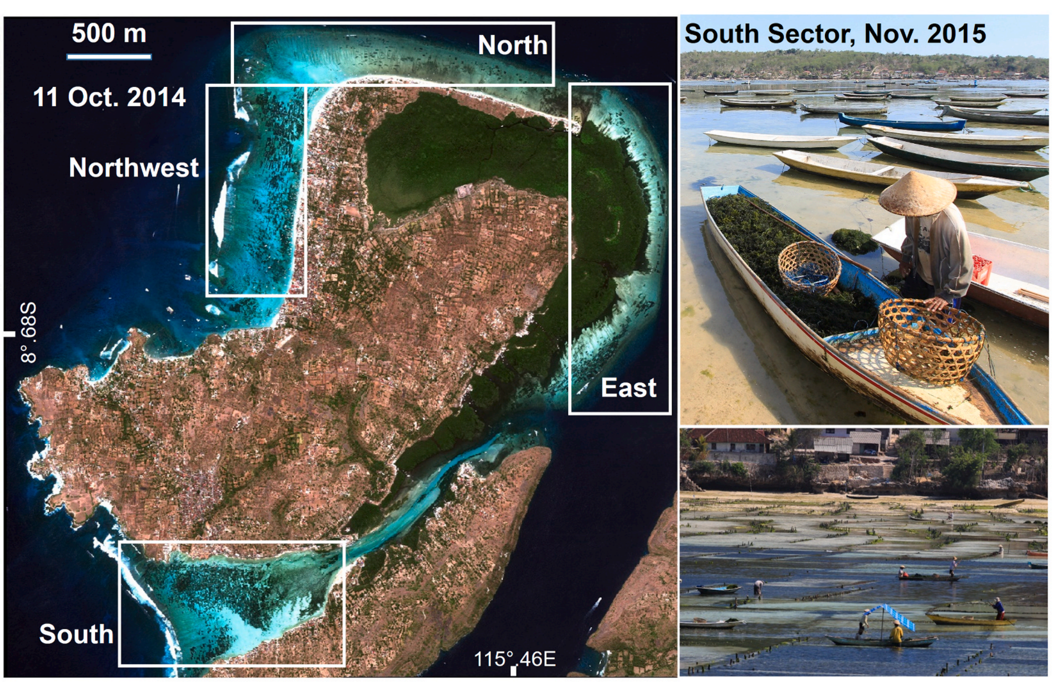

Fig. 2. Left: location of the four studied sectors around Nusa Lembongan, as seen in October 2014 with a Geoeye-1 image. Right: farmers in activity in the South sector in November 2015 (photographs by Serge Andréfouët).

More importantly, considering the high contrast between farmed plots and sand, and the very shallow sites, these corrections are not necessary (Andréfouët 2008). Images were individually processed in digital count units.

To estimate the extent of seaweed farming in each sector (Fig. 2) and for each image (Table 1), we thresholded the green band of each image to create a mask corresponding to the farmed areas at the time of the image acquisition. The sum of the areas identified as farmed plot were divided by the surface area of the corresponding sector to compute a percent cover, hereafter named Seaweed Farming Index (SFI). The value of the green band threshold could be different because all images were of different quality and not radiometrically normalized. The threshold was selected to follow closely on each image the edge of the dark rectangular patches assumed to be farmed plots.

The semi-quantitative SFI score = 5, 4, 3, 2, 1 and 0 reflect that more than >75%, 75-50%, 50-25%, 25-10%, <10%, and 0% of each sector area was covered by farmed plot, respectively. The SFI was deemed sufficient to highlight the collapse of the activity, and its timing for the different sectors (see results).

2.4. Survey of seaweed farmers

The objectives of the survey were to estimate: i) what percentage of informants quit seaweed farming during the 2015–2018 period, when and why did they quit, and towards which types ofactivities did they transfer their effort; ii) the incomes from seaweed farming and from alternative livelihoods following quitting seaweed farming; iii) the intentions (considering the Gunung Agung crisis) to return to seaweed farming as a livelihood. Face to face, unstructured, qualitative surveys (Neuman 2011) took place. First, in February–April 2018, a total of 25 individuals belonging to different Nusa Lembongan and Nusa Ceningan *banjar* were surveyed, men (n = 22) and women (n = 3), known to have work on seaweed farming around Nusa Lembongan (all sectors). In April 2018, twenty-five additional farmers from Nusa Penida, men (n = 20) and women (n = 5), working between Nusa Lembongan and Nusa Ceningan (South Sector) were also surveyed. Each informant represented a separate household. Interviews were conducted in Balinese language by six local surveyors, coordinated by one of us (IMID). Relevant information from the interviews was tabulated in Excel files. Stratification of the survey occurred by villages, but no inferences were attempted to represent the entire Nusa Lembongan (for instance, by estimating the total income at island scale due to the shift of activity) as in Léopold et al. (2014). We considered here the 50 informants to be broadly representative of the different *banjar*. Further, to convert Indonesian Rupiah (IDR) to US dollars (USD), we use the 1 US$ = 14000 IDR change rate (as in December 2020).

3. Results

3.1. Seaweed farming dynamics from satellite imagery

All sectors could be observed with 20 different MAXAR images, although not all sectors were imaged the same day (Fig. 4 and Table 1). Time series of SFI confirmed the collapse of the activity in all sectors (Figs. 3 and 4). The last image suggesting any activity was taken the April 6, 2018 in the south sector. On the ground, in early December 2017, no sign of seaweed farming was visible on the NW, N and NE sectors, and only a handful of boats seemed to work on the south sector,

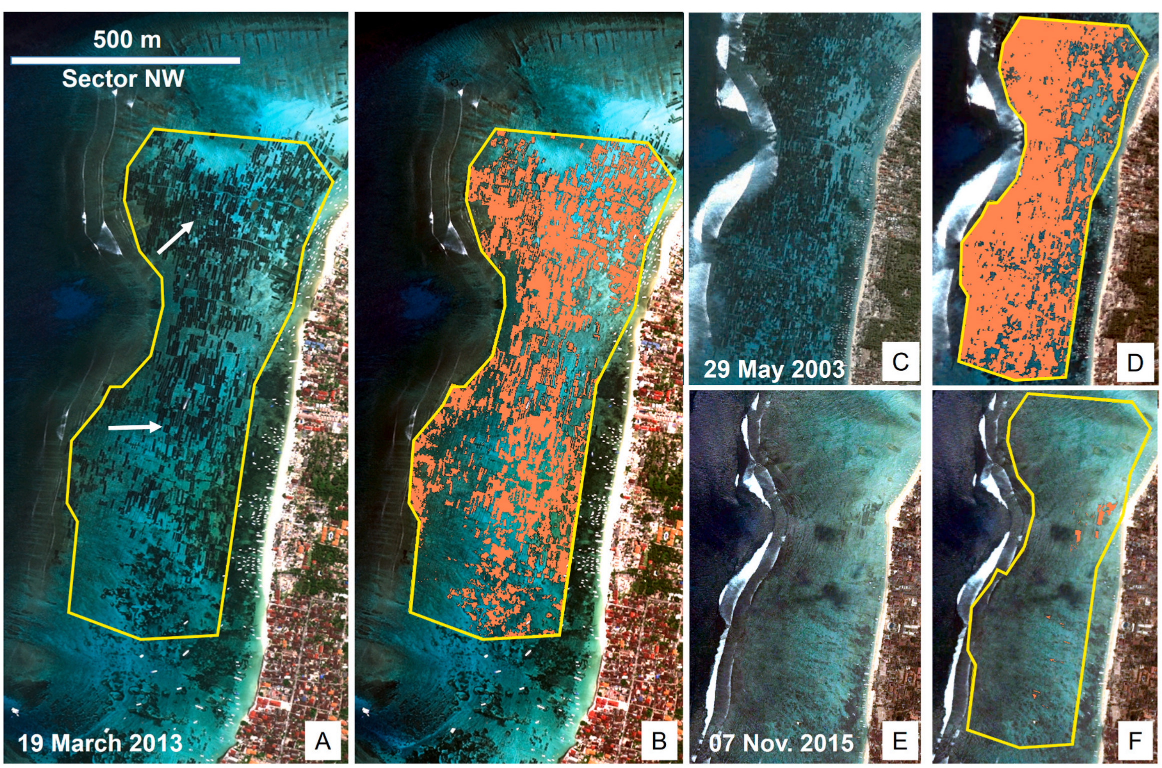

Fig. 3. Illustration, for the northwest sector (Fig. 2), of the dynamics of seaweed farming using 3 different images and years. The yellow polygon represents the area for which the Seaweed Farming Index (SFI) is computed on every image available for this sector. The polygon avoids breaking waves on the reef crest, and dense seagrass beds on the shore. A) Satellite image acquired March 19, 2013. White arrows point to seaweed plots, visible as dark rectangular features, coalescent in some cases. B) Mask (orange) representing the area covered by cultivated seaweed. The ratio of the surface areas covered by the orange mask and the yellow polygon respectively, is 38%, or a SFI = 3. C, D) same as A and B for the May 29, 2003 Maxar (©Google Earth) image. SFI = 5. E-F = same as A and B for the November 7, 2015 Maxar (©Google Earth) image. SFI = 1. On this latter image the large darker patches are cloud shadows, not seaweed plots. The 2003, 2013 and 2015 images summarize the collapse of the activity for this sector (see Fig. 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

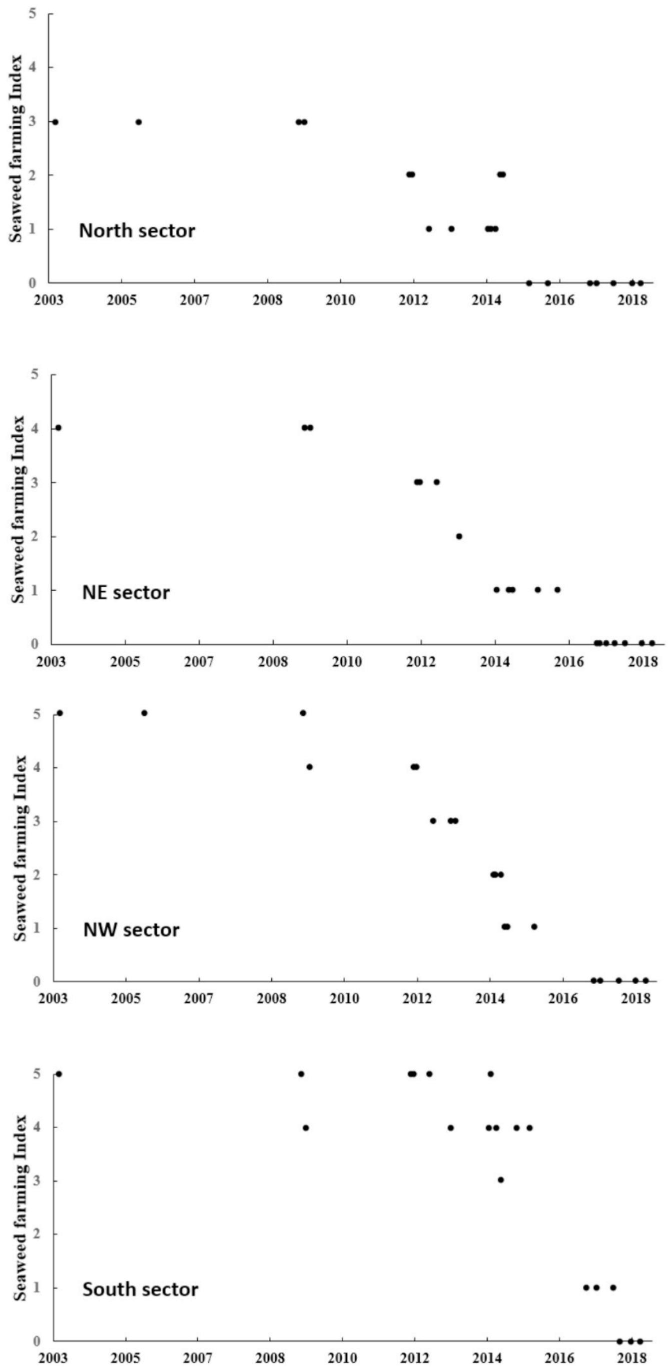

Fig. 4. Evolution of the Seaweed Farming Index for each of the four seaweed farming sectors.

an observation congruent with the satellite images.

The 2003–2019 farming dynamics were different between sectors. The NW and S sectors had the strongest activities before 2009, while sectors N and NE were moderately exploited, and preferentially on the reef flats. On sectors NW, N and NE, the decline started as early as 2009, or at least before 2012 considering the gap in imagery between these two years (Fig. 4). The decline went along a gradual slope and a null-activity level was reached in late 2015. Conversely, for the South sector, the activity was strong till end of 2015, and the collapse went much faster only afterwards (Fig. 4).

3.2. Survey of seaweed farmers

The survey results that could be summarized quantitatively (age, years of work, income when farming, and changes of income after quitting farming) are presented in Fig. 5.

The respondents ranged between 23 and 68 year-old (Fig. 5), with 37 farmers between 30 and 50 year-old. Men were more represented in the surveys (n = 42) than women (n = 8), although we have frequently seen, in 2015 and 2016, women working on the plots, for harvesting, and organizing the drying on shore. The role of women may vary between locations in Indonesia (Waters et al., 2019). The oldest farmer, a woman, said she will not return to seaweed farming because of her age. Before leaving the farming activity, 43 farmers had more than 10 years of experience, 26 had more than 20 years, and 8 had more than 30 years (all reporting to have started in 1983–1985) (Fig. 5).

The survey of the 50 ex-farmers in February–April 2018 showed that they have stopped farming recently (44 farmers stopped after 2014; 19 in 2015 and 18 in 2016). The reasons put forward were primarily failed crops and low selling prices, complicated by some factors such as lack of seeds or shrinking space on the coast to dry seaweed. None of the farmers directly explained their change of activity by tourism or by the lure of easier incomes. However, 24 directly worked for tourism at the time of the survey (including two dive masters), while 17 have turned into full time or part-time construction builder, which is largely driven on the island by tourism development. Other became fisherman (1) and land farmer (8 full time, and 8 part time).

Interestingly, the ex-farmers did not necessarily increase their overall income when shifting activities. When farming was profitable, monthly incomes ranged between 1 and 10 million Indonesian rupiah (IDR) equivalent to ~71–714 USD, with an average ± standard deviation of 3.5 ± 1.3 million IDR (n = 50), or~250 ± 92 USD (Fig. 5). Only 21 Nusa Lembongan farmers specified their new incomes, and 10, 4 and 7 of them earned less, equal, and more with their new activity respectively (Fig. 5). The highest gains were for the two divemasters (doubling or more their salaries). One ex-farmer said he earned 6.5 million IDR less with his tourism activity but this was during the Gunung Agung crisis and not necessarily before it (Fig. 5).

Almost all the respondents working now for tourism also highlighted that their new incomes were lower during the Gunung Agung crisis. Therefore, 14 ex-farmers now involved in tourism considered returning to seaweed farming. An additional large proportion (22 respondents among 50) mentioned they would need strong assurances before returning to seaweed farming, notably higher selling prices. Thirteen respondents said that they will definitely not return to seaweed farming. These answers appeared contrasted between villages. Specifically for the farmers working around Nusa Lembongan (n = 25), all respondents from Junguntbatu (5 total) and Nusa Penida (3) said they will not return to farming. Several of them see the interest of maintaining very small areas of cultured seaweed, but as a tourist activity, not for selling the production. Conversely, all Lembongan informants (5) and almost all (9 out of 12) from Nusa Ceningan said they would return to farming.

4. Discussion

4.1. Semi-quantitative remote sensing for monitoring seaweed farming

Remote sensing is widely used to monitor land cover and land uses, including operational monitoring of agriculture yields (e.g., for rice culture, see the review by Kuenzer and Knauer, 2013) using a variety of sensors, techniques, and at a variety of temporal and spatial scales (Turker and Ozdarici, 2011). The advantages of a remote sensing and spatial approach are numerous, for instance allowing to map the influence of climate on inter-annual yields. Applications for direct monitoring, at very high resolution, of mariculture operations, such as seaweed farming, are far less numerous, but the potential exists to monitor better the production, identify new suitable areas, and like in

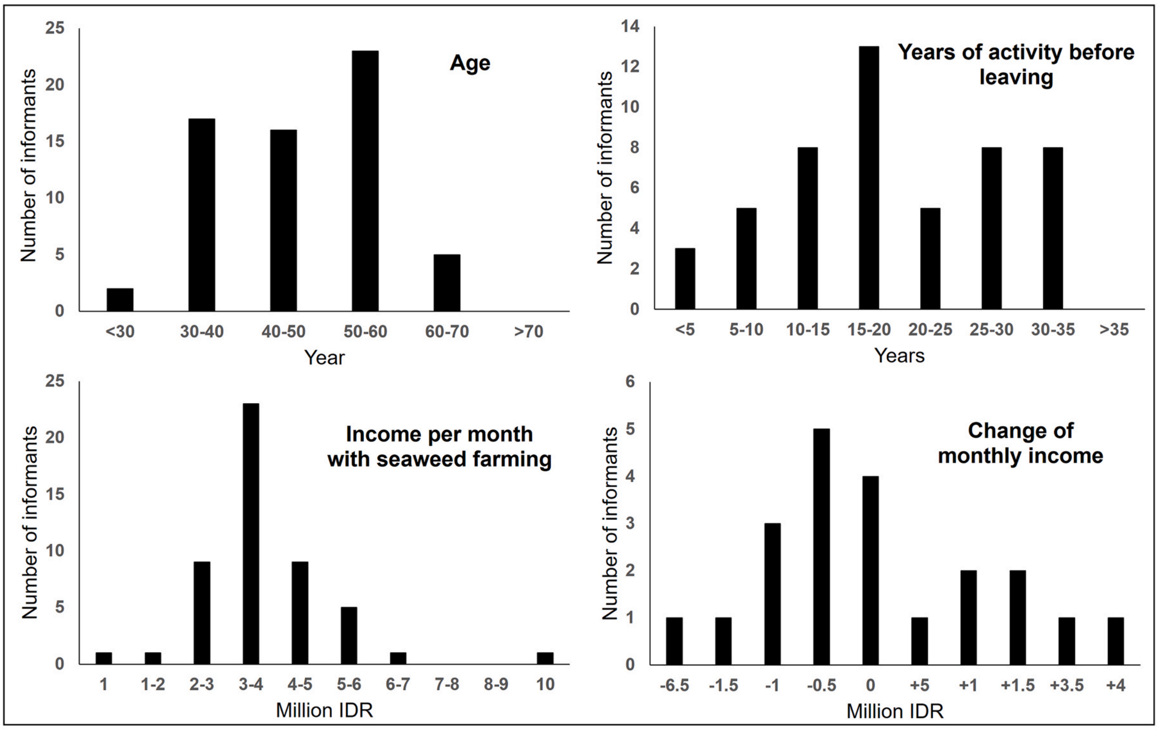

Fig. 5. Histograms summarizing the responses of informants for key variables. n = 50 for all variables, except for change of monthly income (n = 21) (1 USD = 14000 IDR).

our case study, areas that were productive but are not used anymore. The Nusa Lembongan case study showed that VHR remote sensing images, including from Google Earth®, can provide useful early indicators of socio-ecosystems changes, here driven by seaweed farming changes, due to tourism developments, or from other concurrent activities. Around Nusa Lembongan, the trajectories for each sector were slightly different and highlighted different timing and speed of changes (Fig. 4). Considering that seaweed farming is a widespread source of incomes in remote rural areas in Indonesia and South-East Asia (Buschmann et al., 2017), similar monitoring could take place in suitable shallow areas to detect fast, or long-term, alteration of the activities.

Here, the semi-qualitative remote sensing of seaweed farming in very shallow waters was an easy challenge, optically speaking, due to contrasted spatial patterns (Fig. 3). In deeper waters, in case of abundant natural seagrass and macroalgae cover, and for more precise quantitative applications of biomass monitoring (e.g., Setyawidati et al., 2017), remote sensing would be much more challenging and simple processing similar to Nusa Lembongan may not be adequate. Unfortunately, it is not possible to estimate the extent of seaweed farming areas that could be monitored with this technique, in Indonesia or elsewhere. Farmed areas can be shallow, above sand and seagrass areas, and sometimes above coral reef areas (like in Nusa Lembongan but also many areas around Sulawesi or Maluku, pers. observations). Farming can also takes place in deep waters (like in Lombok, or in south Sulawesi, Setyawidati et al., 2017). Floating long lines or off-bottom small plots can be used depending on the locations (Waters et al., 2019). The method applied here would work well for long-lines and off bottom settings in shallow areas dominated by sand, because a strong optical contrast between the farmed areas and the background substrate is needed. How much of the farmed areas these configurations would represent nationally is however unknown.

If the above conditions (depth, type of substrate) are suitable, the very simple methodology used here is reproducible with minimum training, as it does not require any sophisticated software or processing. It can be performed on both calibrated and raw satellite images, or on GE images if costs for image data buy is an issue. We used VHR images (2m resolution), but considering that the required accuracy is low to detect trends with the SFI, the processing would likely be still efficient with 10-m resolution images (like Sentinel 2, which are available at no cost). However, very low, scattered, activity (corresponding to SFI = 1) could be more difficult to detect and could easily yield a SFI = 0. Trials with other type of imagery warrant further investigations.

4.2. Changes exacerbated by tourism market and natural hazards and future management

The importance of livelihood diversification to enhance livelihood resilience is a prominent topic as a strategy to manage both economic and environmental risks (Ellis 2000). Diversification of livelihood activities spreads the risks and reduces their vulnerability and increases resilience to disturbances. Diversification can occur within a sector, like fishery (Bell et al., 2015), between sectors like fishery and mariculture, or mariculture and agriculture (Martin et al., 2013). The changes may be swifter with new generations that have acquired skills that their elders cannot practice (such as scuba diving), or through gender-driven changes (Stacey et al., 2019). In Asian rural communities, seaweed farming is often seen as a way to diversify activities (from fishing for instance), but diversification from seaweed farming is less discussed (Hill et al., 2012; Valderrama et al., 2013). Here, tourism and several other activities provided alternative livelihoods to seaweed farming as it was completely abandoned. However, proper thoughtful and staged planning towards an alternative solution did not take place, which is a recommended strategy (Pomeroy et al., 2017). Strong environmental and market triggers combined with an easy alternative solution explain this. Instead, the shift occurred quickly and it was not long before vulnerability to new disturbances (disruption of tourist flows) was apparent.

According to the survey, several reasons explained the shift from seaweed farming to other activities. Low prices in 2016–2017, down to 2000 Rp per semi-dry (40%) kilo of seaweed instead of typically

15–20,000 IDR (~1.07–1.43 USD)., and unsuccessful crops were pointed out by farmers as the main reasons for quitting farming. Unsuccessful crops were assumed by farmers to be related to unusually high grazing pressure by fishes, in addition to high temperatures and water quality issues. However, these speculative explanations cannot be confirmed by scientific data . Other reasons for giving up the activity were land use changes and shrinking spaces on coastal areas available to dry seaweeds, now used for tourism related activities and development. The growing tourism offered timely new options and some safety for sustained incomes, which likely encouraged the fast abandonment of farming.

The tourist flux in Nusa Lembongan follows the Bali tourism increasing statistics, with record numbers of foreign tourists in 2016 and 2017, exceeding government's previsions and objectives (https://www.balihotelsassociation.com/media-centre/stats/). Also, in 2017, Chinese tourists were more numerous, for the first time, than Australian. We assume that the same trend applied to Nusa Lembongan. Chinese visitors' travels are mostly organized packages from abroad. They are mass-channeled on day-trip tours from Bali to stay few hours on the island on hotels, watersport platforms, and private beaches. It is estimated by these hotel managers that around the Chinese New year, up to 3000 Chinese tourists visited Nusa Lembongan per day. The rest of the year, this number is estimated by local tourist operators and hotels at a maximum of around ~1000 per day (pers. comm.), still a very high number. Therefore, this influx had likely created a high demand for, primarily, local transports (on land and water), but also for staff attending new shops, hotels and restaurant sometimes specifically geared towards the Chinese visitors. This demand combined with usual tourism businesses, can explain the shift of activities by farmers.

The survey, as it was conceived for few specific and fairly urgent questions, could not clarify entirely the variety of incomes within a household, as only ex-farmers were targeted. The collected information provided the household incomes due to seaweed farming when it was profitable, and the income of the informant in his new activity. Hence, the overall level of diversification of activities within a household is not known. We can only know what replaced the farming activity. The similar income achieved by most households with farming when it was profitable and with tourism and other activities later suggests that farmers and their families were not in dire need of higher revenues than when farming was adequate. Instead, this suggests that seaweed farming, when profitable, sustained (or helped sustain if other activities already took place) relatively adequately these families. This confirms that farming is a viable way to sustain rural communities in Indonesia (Blankenhorn, 2007; Aslan et al., 2015; Steenbergen et al., 2017, Waters et al., 2019) and that quitting farming was first due to low prices and possible environmental problems, and not directly because of more lucrative tourism activity. Furthermore, despite the more physically demanding job, a large proportion of ex-farmers considered returning to farming after the Gunung Agung crisis. Other reasons than purely financial can explain this. For instance, the two divemasters who more than doubled their salaries in the dive industry both said they will return to farming if prices for seaweed return to normal values. The cultural and social motivations to return to farming warrant further investigation. Overall, this study also points out to the need to conduct more social and economic in-depth surveys, by integrating ex-farmers but also workers who never worked on farming, especially in the young generations. When combined with remote sensing observations (on seaweed farming plots, but also other indicators such as coastal development and constructions, types of boats, location of boats) understanding of social, cultural and economic processes taking place will be more complete and based on an innovative and spatially-explicit framework.

The results from the surveys suggest that an oscillation of the socio-ecosystem between an almost all-farming and all-tourism options can be expected, with the frequency and amplitude of the oscillations depending on global tourism market, seaweed prices, and natural hazards. While no farming occurred in 2017 and 2018, support by the local government in 2019 allowed 16 farmers to return to farming (IMID, pers. comm.). Furthermore, the price for semi-dry seaweed has bounced back to ~20,000 IDR/kg (or 1.43 USD/kg) and some revival can be expected if this trend is sustained. However, to avoid periods without incomes, population should be informed of the consequences of their choices and encouraged to foresight possible difficulties and therefore prepare for what could be cyclic livelihoods. For instance, the maintenance of know-how and essential gears, material and equipment is required (Steenbergen et al., 2017).

The collapse of farming and the rise of tourism have both positive and negative environmental consequences. Abandonment of farming reduce trampling on the benthic communities present on farmed coral reef flats. Cutting mangroves for wood to farm plots is also likely to decrease. On Nusa Lembongan, most of seafood dishes sold in restaurants come now from Lombok or Bali, as local fishermen have also turned to tourism (pers. observation). Hence, local fish population are probably less harvested at least for commercial purposes. On the other hand, unfortunately, tourism creates other type of disturbances elsewhere, with more, often careless, visitors visiting coral reefs, seagrass beds and mangroves. The moorings of watersport platforms is known to have damaged the benthic communities. Building of roads, shops, restaurants, homestays, and hotels have a toll on the environment, increasing the problem of water access, waste collection and treatment, to name a few of the main issues (Kurniawan et al., 2016b).

The recent dynamics of Nusa Lembongan strongly suggests that the local marine zoning plan needs to be revisited, and that an adaptive management plan will be needed, in agreement with the many local stakeholders involved, at least, in tourism, fishing and seaweed farming. It is obvious that the area reserved for farming in the current zoning plan may be presently unjustified. Instead, without revival of the activity, these often sedimentary and calm areas should now be designed to receive tourists groups, while reinforcing protection of other habitats where biodiversity is high and fragile. The habitat map of Nusa Lembongan, similar to the product done for Bunaken Island by Ampou et al. (2018), can be used to guide such future zoning plan.

Finally, occurring after this study took place, the recent tourism collapse in the wake of the COVID-19 pandemic reinforce some of our recommendations. Bali tourism has collapsed in March 2020 to unprecedented levels and the economic consequences will overshadow the Gunung Agung 2017–2018 crisis (Rahmawati et al., 2019). Planning for alternative livelihoods in complementarity with tourism is now considered at all levels of management (governor, regencies, *banjar*).

5. Conclusion

Fast livelihood shifts similar to what happened, and is still happening, in Nusa Lembongan are likely in Indonesia, whether they are triggered by climate change, policy and planning, market prices, tourism, development opportunities, natural hazards, pandemics, or a combination of these factors. It has long been advocated that monitoring the often complex socio-ecosystems dynamics should be a priority for coastal zone management, within or outside marine reserves. This recommendation remains particularly acute. In particular, as emphasized by Steenbergen et al. (2017) management should ensure that new activities are not susceptible of abrupt interruptions, after which the local population could be left without viable options. In Nusa Lembongan dynamic environments of change, and also elsewhere in Indonesia and Asia, more in-depth surveys on the perceptions of local actors could have provided a much better triangulation of the findings than what we could report here following a much targeted survey that was driven by a specific event. The need for more comprehensive qualitative understanding of the change observed and the perceptions of change by local actors will be useful for future similar studies on the dynamics of socio-ecosystems. Populations should also be aware of the consequences of their choices and encouraged to foresight possible difficulties and adaptations to cyclic livelihoods. For managers in charge of large remote areas, remote sensing can contribute in some cases to monitoring, even with very simple processing techniques, as shown here. This study expands the number of coastal zones where historical changes could be reconstructed using satellite images (e.g., Gusmawati et al., 2018). Other Indonesian sites could be shortly investigated to further assess the potential of remote sensing to monitor small island socio-ecosystem changes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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