Efficiency and sustainability of land-resource use on a small island

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Abstract

Land resources are essential for humans to survive, and different methods of land-resource use depend largely on the local natural context and society. Here we propose a method to assess land-resource use in terms of efficiency and sustainability for three historical types of land-resource use in the Babeldaob Island, Republic of Palau: self-supply, resource development and nature conservation. Our proposed index of land-use efficiency makes comparisons possible among the types of land-resource use, considering both the natural and social conditions; land-use efficiency increased in the order of self-supply, nature conservation and resource development. At the same time, sustainability of land-resource use corresponded to population growth; when the population density was less or more than 15 capita km⁻², self-supply and nature conservation were the most sustainable, respectively.

1. Introduction

Land use is a planetary boundary that defines the safe operating space for humanity with respect to the Earth’s systems [1]. The Food and Agricultural Organization defines land and land resources as follows: ‘Land and Land Resources refer to a delineable area of the Earth’s terrestrial surface, encompassing all attributes of the biosphere…, the soil and terrain forms, the surface hydrology…, the near-surface sedimentary layers…, the plant and animal populations, the human settlement pattern and physical results of past and present human activity…’ [2]. This complicated definition includes various types of land resources composed not only of natural systems but also those relating to human activity.

Food production is a major demand made on land resources by humans, and the total area of cropland in 2015 was 1.59 billion ha (12.5% of the total land) [3]. As a result, agriculture is now the main factor underlying many environmental threats, including climate change, biodiversity loss and degradation of land and freshwater habitats [4].

Much research exists on the impact of land use on the environment and how economic globalization has affected the local environment. The conclusion reached is that excessive consumption in advanced and rapidly emerging economies drives environmental loss in developing nations in terms of greenhouse gas emissions [5, 6], loss of biodiversity [7, 8] or water scarcity [9, 10].

In 1996, Allan [11] proposed the original concept of ‘virtual water’ and suggested that importing water-intensive commodities could provide a solution for the regional deficits in water-poor nations, and he termed this virtual water as ‘a strategic resource’. Oki et al analyzed the relationship between renewable water resources and GDP per capita and suggested two types of strategies for sustainable development from the perspective of water stress: some countries with abundant water resources could focus on developing water resources and producing water-intensive commodities for export, and others, with scarce water resources, ought not to focus on developing water resources but, rather, on commodities that required less water to improve their GDP [12]. The land is similar to water in the sense that it is a local and immovable resource and should be discussed in terms of ‘strategies’ based on the local natural and social conditions.

Small island developing states face challenges to achieve sustainable development goals (SDGs) where
their natural, economic and social systems are vulnerable [13]. The IPCC AR5 WGII report [14] highlights the risks of climate change, which include the loss of adaptive capacity and ecosystems that are critical to the lives and livelihoods of people living on small islands. Some of the natural conditions on small islands not only highlight the vulnerabilities but also complicate their ability to adapt to future changes and achieve their SDGs; one of the major characteristics is the limited availability of resources. Available resources are scarce in the Pacific Islands and since they depend on external regions for essential materials, the impacts of future climate change and socio-economic changes are more severe compared to other regions [15, 16]. Moreover, since tourism is their main resource for economic growth, and many tourists visit for the beautiful and natural environment, these resources are very vulnerable to social and climate changes [17].

In the South Pacific Islands where the topography is steep and annual rainfall is high, the use of excessive resources due to human activity accelerates the flow of eroded soil and nutrients into the sea, reducing the sustainability of the ecosystems and substance circulation [18–20]. The transport duration of this eroded sediment to the coastal regions is shorter and the sediment concentration is higher for the islands than for continents, due to the former having smaller watershed areas. Consequently, these large amounts of sediment disturb the aquatic ecosystems, including those of the corals [21]. Currently, 50% of the coral reefs in the Pacific region are in danger and half of these have been impacted by the environmental load from the land [22]. Soil and nutrients flowing from the land can lead to a loss of diversity in coral reef ecosystems in particular [23].

In this study, Babeldaob Island in the Republic of Palau has been used as an example to highlight the efficiency and sustainability of land resource use, as seen by the impact of long-term shifts in land-resource use on the aquatic environment on a small island. The land-resource use is prescribed by the social situation as well as by the availability of the natural resources. We compare three different forms of land-resource use based on historical maps. As an indicator of the environmental impact, we used sediment yield that has flowed into the coral reef, which is a typical problem for small islands in terms of natural vulnerability and economic profitability.

2. Methodology

2.1. Target area

The Republic of Palau, where this research took place, is undergoing economic development through tourism and advanced initiatives including regulation and policies relating to preservation of the environment [24].

Babeldaob Island in the Republic of Palau was the focus of this research (figure 1). The Republic of Palau is formed of 568 islands; Babeldaob has the largest area, at 365 km², which is equivalent to approximately

![Figure 1. Location of the Republic of Palau (left) and the target watersheds on Babeldaob Island. Grouped zones (i)–(iv) surrounded by a red line show the watersheds with historical population data. Shaded area indicates the Ngerliil River watershed used for calibration and validation of the model.](image-url)
80% of the total national land. There are mountains in the north, south and central regions, and major river basins flow into the bays on the east and west coasts. It has a tropical climate, which is warm throughout the year, with an average annual temperature of 28 °C. The average annual precipitation is 3800 mm; the dry season is from December to April and the rainy season is from May to November. The population of the Republic of Palau was ∼22,000 in 2018 and the GDP per capita was US$14,428 in 2016 [25]. The main industry consists of tourism-related activities that are dependent on natural resources such as the beautiful coral reefs, beaches, waterfalls, etc.

Life on Babeldaob Island has been sustained for at least 1000 years, implying that the population have been able to survive and prosper with its main food source being the starch from taro fields and protein from reef fishes [26]. Land development due to human activities caused increased sediment runoff into the ocean and this, in turn, reduced coral cover biodiversity [27, 28]. The form of land-resource use on Babeldaob Island changed over time from self-supply (1921) to resource development (1947) and, finally, to nature conservation (2012), which supports the more recent promotion of tourism in the 21st century [29]. The land-use data for self-supply, resource development, and nature conservation are shown in figure 2. Here, agroforestry refers to extensive multi-layered farming in the forests surrounding the villages. In self-supply, the residents preserved their livelihoods via hunting, gathering and extensive farming. During the period of Japanese rule from 1914 to 1945, industries relating to resource development advanced, particularly mining and agriculture, and forests were reclaimed to create barrens or farmlands. From 1921 to 1947, forested areas were reduced by 50 km² and grasslands increased by 39 km². In the 21st century, nature conservation has been promoted due to the emergence of responsible tourism [30]. From 1947 to 2012, forested areas increased by 39 km² and urban areas merged to an area of 8 km².

Watersheds containing population data for all three forms of land-resource use were grouped into four zones according to the boundary shown in figure 1. Table 1 lists the population history and land use in each zone. In 1921, Palauan villages were present in all zones. A privately-owned Japanese copra plantation was located in zone (i), but the island was not extensively developed. Following the 1923–1927 land survey carried out by the Japanese government, industrial development was started. By the end of the Second World War in 1945, there was a Japanese plantation village and military installations, including an airport and a navy base in zone (i); an official agricultural experimental farm was established and farming trials were conducted in zone (ii) and bauxite mining sites were developed in zones (iii) and (iv). After the war, the copra plantation became
Table 1. Population and land-use history of each zone.

| Zone (i) | Zone (ii) | Zone (iii) | Zone (iv) |
|----------|-----------|------------|-----------|
| 1921     | Palauan villages | Palauan villages | Palauan villages |
| Population | 322 | 215 | 196 | 110 |
| Land use | Japanese copra plantation | Palauan villages | Palauan villages | Palauan villages |
| 1947     | Palauan villages | Palauan villages | Palauan villages |
| Population | 922 | 368 | 1598 | 1953 |
| Land use | Palauan villages | Palauan villages | Japanese agricultural experimental farm |
| Japanese copra farm | Palauan villages | Japanese bauxite mining (1938–1942) | Palauan villages |
| Japanese plantations | Palauan villages | Japanese bauxite mining (1940–1945) | |
| Japanese military installations | | | |
| 2006     | Palauan villages | Palauan villages | Palauan villages |
| Population | 2723 | 734 | 317 | 166 |
| Land use | Palauan villages | Palauan villages | Palauan villages |
| New subdivisions | Bureau of Agriculture | | |
| Private commercial farms | | | |

By 1947, some of the Palauan villages had disappeared from zones (ii), (iii), and (iv), in contrast to the new areas of residence that had been developed by the state government in zone (i).

2.2. Simulation settings

The Soil and Water Assessment Tool (SWAT) is a water and material dynamics analysis model that considers hydrological processes [31]. The SWAT model can be used to evaluate the impact of material movements at a basin such as water, sediment and nutrients derived from human activities such as farming and land use. SWAT is composed of sub-models that make daily analysis assumptions. This makes SWAT unsuitable for flood routing within a rainfall event, but more useful for long-term analyses. In recent years, SWAT has been applied to basins in developing countries where sufficient monitoring data are not available, such as in south-east Asia [32, 33], but there are very few examples of it being applied to countries in the South Pacific Islands, including the Republic of Palau [34]. We used ArcSWAT ver. 2012.10.1.13 in this study.

Watersheds were delineated based on a digital elevation model [35]. The unit catchment area for flow accumulation was set to 0.1 km². The target area of this study was divided into 24 watersheds composed of 1108 sub-basins around Babeldaob Island and the total area was 239 km², which was equivalent to 65% of the entire island. The target watersheds were selected in order of size, and watersheds with notable changes in land use were also included regardless of the size of the catchment area. The basin boundaries of the 24 watersheds are indicated by solid lines in figure 1.

Hydrologic response units (HRUs) were defined based on soil maps, land-use maps in the form of land-resource use and topography. The soil map of the National Resources Conservation Service, United States Department of Agriculture (NRCS, USDA) [36] and three land-use maps [29] were adopted. Table 2 lists the relationship between the land-use category in figure 2 and the SWAT land-use code. The single and mean slopes in each sub-basin were adopted as the topographical parameters. Thresholds of land use and soil were set to 10% and 45%, respectively, and the number of HRUs were 1617 (1921), 2039 (1947) and 1968 (2012).

Table 2. Correspondence between land use category and SWAT code.

| Land use category | SWAT code | Description |
|-------------------|-----------|-------------|
| Mangrove          | WETF      | Wetlands-forested |
| Water             | WATR      | Water |
| Grassland         | PAST      | Pasture |
| Urban             | URBN      | Residential |
| Farmland          | AGRR      | Agricultural land-row crops |
| Agroforestry      | FRST      | Forest-mixed |
| Forest            | FRSE      | Forest-evergreen |
Table 3. Calibrated parameters and optimized values of SWAT.

| Parameter | Description                                      | Optimized value |
|-----------|--------------------------------------------------|-----------------|
| Discharge parameters |                                                  |                 |
| ALPHA_BF  | Base flow recession constant                    | 0.94            |
| CH_K2     | Effective hydraulic conductivity of channel (mm h⁻¹) | 360             |
| GWQMN     | Threshold water depth in the shallow aquifer for base flow (mm) | 4300           |
| ESCO      | Soil evaporation compensation coefficient       | 0.21            |
| GW_REVAP  | Groundwater revap coefficient                   | 0.066           |
| CH_N2     | Manning’s n value                               | 0.016           |
| Sediment parameters |                                                |                 |
| SPCON     | Linear parameter                                | 0.001           |
| SPEXP     | Exponent parameter                              | 1.1             |
| PRF       | Peak rate adjustment factor                     | 0.088           |

calibration [39]; the calibrated parameters are listed in table 3. The parameters were selected after referring to those in Noda et al [40], with a common value that did not relate to land use and soil properties.

Observation data from the Ngerikiil basin, located in the southeast of Babeldaob Island, between 2011 and 2012 [41] were used for calibration and validation. The monitoring systems we used in the Ngerikiil basin (0.99 km²) consisted of a rain gauge, water level sensor, water velocimeter, and turbidity sensor. A rain gauge (RG3-M, Onset Computer Corporation, Bourne, MA, USA) was placed in the basin (figure 1) to measure precipitation. A water level sensor (U20-001-04, Onset Computer Corporation, Bourne, MA, USA) was attached to the steel pipe which was stabbed into the riverbed. The water level sensor recorded pressure, which was converted into water depth. A two-dimension electromagnetic water velocimeter (Compact-EM, JFE Advantech Co. Ltd, Nishinomiya, Hyogo, Japan) was attached to the submerged pipe to measure the flow velocity. Water discharge was determined by using the flow cross-sectional area calculated from water depth and transversal river bed topography; the velocity profile derived from the measured flow velocity was assumed to be logarithmic. An infrared back-scattering type turbidity sensor (Compact-CLW, JFE Advantech Co. Ltd, Nishinomiya, Hyogo, Japan) was attached to the submerged pipe to estimate the suspended sediment concentration (SSC). These instruments were installed in the Ngerikiil River in January 2011; they remained operative until the end of 2012. Measurements were made and recorded with instruments at intervals of 10 min. Continuous water discharge was estimated with a H–Q curve ($R^2 = 0.975$), which was drawn from flow velocities and water depths. Continuous SSC were estimated via a calibration curve ($R^2 = 0.989$) with turbidity as the independent variable and SSC of discrete water samples as the dependent variable. Finally, continuous sediment runoff rate was calculated by multiplying the continuous water discharge by the continuous SSC. During this period, days on which the daily discharge was in the $H–Q$ curve range (0.07–0.61 m³ s⁻¹) were selected and these data were specifically used for calculation and validation. The data period was divided into two phases; data from 2011 were used for calibration and those from 2012 were used for validation. The land-use data used for calibration and validation were taken during the nature conservation period (2012). For the weather data, precipitation data were used from 2011 and 2012 [41]; other available datasets covering 10 years were used for the remaining parameters, including temperature, humidity, wind speed and solar radiation. 10 year runs were conducted using the same daily precipitation over a single year, which was repeated while the other parameters were changed, and the average outputs were compared to the observational data.

Calibration was performed in two steps: (1) calibration of parameters related to river discharge and, (2) calibration of parameters related to sediment flow. The parameter ranges were optimized with a 95% confidence interval of the best solution, after 1000 iterations in a step to maximize the Nash–Sutcliffe efficiency (NSE) [42]. The parameter ranges were updated until the model outputs satisfied the criteria in Moriasi et al [43], using NSE, the percent bias (PBIAS) [44], and the ratio of the root mean square error to the standard deviation of the measured data (RSR) [45].

2.3. Efficiency and sustainability of land-resource use

Walling proposed population growth as a useful alternative index to the driving force of sediment runoff increase in developing countries, based on long-term monitoring data from rivers around the world; changes in land-resource use, such as land development for food production, cash-crop cultivation, mining, building and social infrastructures accompany population growth, and lead to an increase in sediment runoff [46]. Based on the above, Noda et al formulated a relationship between the rate of population growth and that of increased sediment runoff in a first-order approximation [34], which is shown by the following equation:

$$\frac{dS}{S} = \frac{dP}{P},$$

(1)

where $S$ is the annual sediment yield (tons ha⁻¹ yr⁻¹), $P$ is population density (capita ha⁻¹), and $a$ is a positive constant, which indicates the land-use efficiency defined by a ratio of the rate of increase in annual sediment yield to the rate of population increase. The value of $a$ due to forest development in the 20th century in developing countries of south-east Asia is
but there is no information regarding the long-term change of the value of $a$. Solving equation (1) gives $S$ as the following equation:

$$S = b \times P^a,$$

where $b$ is a positive constant. Parameters $a$ and $b$ are determined by the local, natural and social conditions. According to Walling’s explanation [46], the smaller value of $a$ can be interpreted as land use being more efficient. At the same time, it is possible to find the sustainable form of the land-resource use that corresponds to population level by comparing the curves of equation (2) in various forms of land-resource use; the lower value of $S$ indicates that the land-resource use is more sustainable.

### 3. Results and discussions

#### 3.1. Calibration and validation of SWAT simulation

We performed two calibration steps of 1000 iterations for river discharge and five calibration steps for sediment flow; the calibrated values at the last step are listed in table 3. Monthly river discharge and sediment flow for the calculations and observations are shown in figure 3. The line of calculation indicates the SWAT output using the best parameters after calibration. The annual variations both in river discharge and sediment flow were accurately simulated during the calibration periods; at the last calibration step, $\text{NSE} = 0.79$, $\text{RSR} = 0.46$, and $\text{PBIAS} = -0.46$ for river discharge and sediment flow, and $\text{NSE} = 0.81$, $\text{RSR} = 0.43$ and $\text{PBIAS} = -6.0$ were rated as very good by the criteria in Moriasi et al [43]. The validation for sediment flow (figure 3(d)), $\text{NSE} = 0.85$, $\text{RSR} = 0.39$, and $\text{PBIAS} = -1.1$ were also rated as very good [43]. These values indicated that the SWAT outputs for sediment flow were valid for the monthly variations as well as for the annual average. On the other hand, the validations for sediment flow, $\text{NSE} = 0.92$ and $\text{RSR} = 0.15$ were rated as unsatisfactory and only $\text{PBIAS} = -17.1$ was rated as satisfactory [43]. These values indicated that the SWAT outputs for river discharge were not valid for monthly variations, but were valid for the annual average. The annual precipitation during those periods was 4724 mm in 2011 and 3636 mm in 2012; the former
was much higher than the annual average, whereas the latter was slightly lower. The calibrated settings of SWAT were valid for river discharge and sediment flow in higher-than-average and average years when sediment runoff was significant.

3.2. Spatial distribution and long term shift of sediment yield
The annual average sediment yields in the form of land-resource use are shown in figures 4 and 5. The averages for self-supply, resource development, and nature conservation were 1.9 tons ha\(^{-1}\) yr\(^{-1}\), 5.9 tons ha\(^{-1}\) yr\(^{-1}\) and 4.1 tons ha\(^{-1}\) yr\(^{-1}\), respectively.

From 1921 to 1947, between the eras of self-supply and resource development, sediment yield increased by an average of 4.0 tons ha\(^{-1}\) yr\(^{-1}\). A large area of forestry was turned into grassland and farmland (figure 2) and sediment yield increased in 21 out of 24 watersheds (figure 5). In the watersheds of zones (i)–(iv) in particular, sediment yields increased, especially in the inland

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**Figure 4.** Spatial distribution of sediment yield from sub-basins in 1921 (self-supply), 1947 (resource development) and 2012 (natural conservation).

**Figure 5.** Boxplot of sediment yield from subbasins in 1921 (self-supply), 1947 (resource development) and 2012 (natural conservation). The upper end of the whisker represents the maximum. The bottom, top and middle line of the box represent the first and third quartiles, and the median, respectively.
areas of the island (figure 4) because of agricultural development in zones (i) and (ii) and bauxite mining in zones (iii) and (iv) during the period of Japanese rule [29].

From 1947 to 2012, during the eras of resource development to nature conservation, sediment yield decreased by an average of 1.8 tons ha$^{-1}$ yr$^{-1}$. The sediment yield decreased in 21 watersheds but in 13 of these 21, it remained at a higher level compared to 1921 (figure 5). Since the end of Japanese governance, a large area of farmland and the mines were abandoned and have been returning to forestry or grasslands, as shown in figure 2 [48]. In addition, nature preservation efforts increased on a national basis after independence in 1994 [24] and these have contributed to maintaining and increasing the area of forest. Sub-basins, where the sediment yield had decreased, were located in inland and coastal areas (figure 4). Although the average sediment yield has decreased and has started to return to previous levels, more time is needed for grasslands to turn to forest, as was present previously. On the other hand, in 2012 some portions of zone (iv), which were previously bauxite mining sites, remain barren, although the barren area has decreased since 1947. It will take more time to recover the land in those sub-basins because the topography is very steep and the rich surface soil has already been washed away. Today, the area remains barren but does not yield very much sediment [27]. Therefore, the sediment yields in the sub-basins in zone (iv), which include the barren areas, could have been overestimated in 2012 because the same parameters of freshly cultivated areas were applied to the barren areas in this analysis.

3.3. Efficiency and sustainability of land-resource use

The relationship between population density and sediment yield in zones (i)–(iv) are shown in figure 6. The value of sediment yield of zone (iv) in 2012 was adjusted to exclude the sub-basins with barren areas, which created an overestimation on sediment yield, as discussed above, and the value is shown as a white outlined plot.

In figure 6, the curve of 1921 increased rapidly, but the plots gathered towards the bottom left-hand side. This suggests that population growth in the form of self-supply could have brought about a large increase in sediment yield, but this did not actually occur. Both the land and the reef were important for food production and the sustainability of the reef fisheries must have required the reef to be sheltered from excessive soil erosion [26]. This ensured that the sediment yield remained low, as did the population. Sediment yield was >8.0 tons ha$^{-1}$ for resource development but the curve increased moderately according to the increase in population density. Agriculture and mining during resource development created products for export and were independent of the local population but dependent on the availability of resources. The nature conservation curve also increased moderately; the plots distributed in the range between the plots in the form of the self-supply and resource development in figure 6. Forested areas have increased (as discussed in section 3.2) and the amount of sediment yield is expected to decrease in the future.

While population density increased from 1921 to 2012, except in zones (iii) and (iv), where there were over 1000 foreigners in 1947, the order of the value of $a$ was self-supply, nature conservation and resource development; self-supply was worse than resource development. This may seem unexpected but is actually reasonable because the population capacity of a self-supplying society is smaller than the others since the available resources are limited where they live, and they rely on imported food produced from outside of the island.

This result was not consistent with Walling’s description [46], which implies that the value of $a$ is likely to increase in stages due to changes in the form of land-resource use accompanying population increases. The values of $a$ were all much smaller than in Abernethy’s assumption estimated for rivers in Southeast Asia [47]. These differences were presumably derived from the basin characteristics of the river basins; we focused on the rivers on a small island.
but Walling and Abernethy analyzed large rivers in continents [46,47].

The curves in figure 6 also suggested a sustainable path of land-resource use corresponding to population growth. The curves of self-supply and nature conservation crossed at the population density and sediment yield was 15 capita km$^{-2}$ and 4.1 ton ha$^{-1}$; it suggested self-supply was the most sustainable when the population density was less than 15 capita km$^{-2}$ and nature conservation was the most sustainable when the population density was more than 15 capita km$^{-2}$. Resource development was not a reasonable choice at any population density level, even though the land use was most efficient according to parameter a. The positional relationship of the curves is also dependent on the values of parameter b. The value of b is generally assumed to be larger in small islands because of the steep topography and the high volume of precipitation but the solution for sustainable development can be different in other islands.

These results suggested that, on small islands, economic growth dependent on resource development reduces the sustainability of the land-resource use and that promotion of nature-based tourism, which is currently the main industry in the Republic of Palau, contributes not only to economic growth but also to improvement of land-resource use sustainability. It should be noted, however, that this is the result of high dependency on resources from outside the islands, namely Palau, that protects the inland resources, and this could cause other issues with regard to Palau’s importation of food and materials. This trade-off should be investigated further.

4. Conclusion

In this study, Babeldaob Island in the Republic of Palau has been used as an example to highlight the efficiency and sustainability of land resource use, as seen by the impact of long-term shifts in land-resource use on the aquatic environment on a small island. We compare three different forms of land-resource use based on historical maps. As an indicator of the environmental impact, we used sediment yield that has flowed into the coral reef, which is a typical problem for small islands in terms of natural vulnerability and economic profitability.

Our proposed index of land-use efficiency makes comparisons possible of the types of land-resource use, considering both natural and social conditions; land-use efficiency increased in the order of self-supply, nature conservation and resource development. At the same time, sustainability of land-resource use corresponded to population growth; when the population density was less or more than 15 capita km$^{-2}$, self-supply and nature conservation were the most sustainable, respectively.

We expected our findings will support future discussions of land-resource use or ‘land-use strategies’ on a global level and will consider local stakeholders. It should be noted that our analysis is based on the historical shift of society in the Republic of Palau but the path is not always as simple in other countries. Additional data collection and analysis are expected to validate the relationship between social development and land-use efficiency on small islands.

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Author Contributions

KN designed the study, conducted data analysis and wrote the paper with contributions from all authors. AI, SW, and KO developed land use, weather forcing and hydrological observation data, respectively.

Competing interests

The authors declare no competing interest.

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