

The Bio Economic Seaweed Model (BESeM) for Modeling *Kappaphycus* Cultivation in Indonesia

P. A. J. van Oort , Nita Rukminasari , Gunarto Latama, Jan Verhagen, and A. van der Werf

Abstract

A simple model was presented for simulating production and economics of tropical seaweed cultivation. The model has a limited number of parameters, which makes it easily amenable to other seaweeds and other sites. Parameter estimates were presented and uncertainties in parameter estimation were discussed. A simulation example suggests farmers can increase income by using cuttings with a higher weight than they are currently using. A literature review suggests still much need for further experimentation.

Keywords

Simulation · Model · Production · Economics · Seaweed

8.1 Introduction

Seaweed farming is an important source of income for coastal communities in Indonesia and other tropical countries and a growing economic sector for decades (FAO 2018). Common tropical (red) seaweeds cultivated in Indonesia are *Gracilaria*, *Kappaphycus alvarezii* (cottonii), and *Eucheuma denticulatum* (spinosum). Important producers are India (Periyasamy and Rao 2017; Periyasamy et al. 2019), Indonesia (Setyawidati et al. 2017; Kasim et al. 2016), Malaysia (Phang et al. 2019), the Philippines (Dawes et al. 1994), and Vietnam (Bui et al. 2019). Seaweed growth in these tropical countries is markedly different from that in temperate climates. In temperate climates, for the example case, only one seaweed crop is grown per year, or two

distinct seaweeds such as *Saccharina* in winter and *Ulva* in summer. Whereas in the tropics the same seaweed species is cultivated a number of times per year and year after year. In temperate climates, seaweed farms buy inoculated lines from companies specialized in seaweed propagation. In tropical climates cultivation is predominantly through on-farm, vegetative replanting part of the harvested seaweed. Most commonly in the tropics, seaweeds are cultivated in cycles of 45 days. A line is planted out and harvested after 45 days. The harvested seaweed is separated in two piles, one large pile to be dried and sold, a smaller part to be replanted. The replanted part then starts a new cycle of 45 days and so forth. Figure 8.1 provides an image of different steps in the cultivation cycle in Sulawesi, Indonesia. The FAO report by (McHugh 2003) provides a more elaborated overview of tropical seaweed cultivation in various countries.

It is unclear if, and how, current farm management practices can be improved. Consider a cultivation period of a year, 360 days. Is a farmer better off with 12 cycles of 30 days, 8 cycles of 45 days, or 6 cycles of 60 days? (note in all cases cultivation is for 360 days). While yield per harvest will normally be higher with a longer cycle, aggregate yield (over a year) might be higher with more, yet shorter cycles. A second important operational farm management decision is how to split up harvests into the fraction sold and the fraction replanted. Selling a large fraction of the harvest (say 90%) may seem attractive to the farmer. Imagine a harvest of 1 ton/ha at a selling fraction of 90%; in this scenario, the farmer sells 0.9 t/ha and replants 0.1 t/ha. A low replanting weight results in slow initial growth. Imagine harvest would be 1.6 t/ha at a selling fraction of 75%. In this second scenario, the farmer sells $1.6 \cdot 0.75 = 1.2$ t/ha and replants $0.25 \cdot 1.6 = 0.4$ t/ha. Total sales are then higher (1.2 t/ha vs. 0.9 t/ha), despite the fact that a smaller fraction of the harvest is sold (75% vs. 90%). Ultimately, farmers are more interested in net profit than in yield. The cultivation system is very labor intensive, but in a peaked manner. That is, almost no labor is needed while the seaweed is out in the sea growing

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Fig. 8.1 Pictures of typical seaweed cultivation in South West Sulawesi, Indonesia. Top left: seaweed is growing on lines in between wooden poles. Top right: seaweed is harvested by boat. Bottom left:

seaweed to be sold is dried on platforms on the beach. Bottom right: seaweed sorting and tying up new lines is a labor-intensive process. Photos by Dr P.A.J. van Oort, 2019

on its line. A peak in labor demand occurs on the day of harvesting. That day, the seaweed is harvested, sorted into the two piles (sales and replants); the sales pile is placed on platforms for drying; the replant file is sorted into individual plants (in Indonesian Bahasa: bibit), which are attached to a new clean line; and these new lines are set up in the sea again. Depending on farm labor availability and costs, it may be more profitable for farmers to adopt a longer growing period (thus less harvests and less peak labor costs within 1 year), despite the lower aggregate yield associated with longer cycles.

The farm management decisions, which we discussed above, can be investigated purely experimentally. Describing these management decisions in a mathematical model offers significant benefits. Modeling can be useful for summarizing current knowledge and for identifying knowledge gaps. Modeling can be a way to integrate knowledge from different domains, such as biology and economy. Finally, once a model has been successfully validated, it can be used to compare management decisions such as those discussed above. We will present example comparisons in this chapter.

For temperate climates, recent advances have been made in seaweed modeling (Broch and Slagstad 2012; Duarte and Ferreira 1997; Jackson 1987; Lavaud et al. 2020; van der Molen et al. 2018; Venolia et al. 2020; Zhang et al. 2016).

Modifying these models to a tropical context is quite impossible, because they require so many input parameters, while generally very limited experimental data are available from tropical seaweed cultivation systems. The most commonly used model in tropical seaweed studies in India, Indonesia, and the Philippines is the exponential growth model (Dawes et al. 1994; Dawes et al. 1993; Kasim et al. 2016; Periyasamy et al. 2019; Setyawidati et al. 2017; Hurtado et al. 2001), in which fresh weight $w_f(t) = w_{f,0} * \exp(RGR * t)$ increases exponentially over time t since planting with relative growth rate RGR ($g\ g^{-1}\ day^{-1}$). An obvious limitation of this model is that it is only useful for describing the initial growth phase of a seaweed, which is indeed often exponential. Species do not continue growing exponentially forever. This is reflected in lower RGR values reported when a seaweed is grown for a longer period of time (Kasim et al. 2016; Periyasamy et al. 2019). Furthermore, all these biological studies lack an economic component. In turn, the few studies on tropical seaweed farm economics (Tahang et al. 2019; Limi et al. 2018) lack a biological component.

There is a need for a seaweed growth model positioned somewhere in between the complex biological models developed for the temperate climates and the simple exponential growth model, in combination with economics of seaweed cultivation. The objective of this chapter is to present such a

model. The following part of this chapter contains two main sections. In Sect. 8.2, we present the BESeM model, and in Sect. 8.3, we present example simulations. We conclude the chapter with a discussion.

8.2 Bio Economic Seaweed Model (BESeM)

We start with listing model variables and parameters. The Bio Economic Seaweed Model (BESeM) consists of a biological module and an economic module. In the model, most variables and parameters are expressed per square meter; in Sect. 8.2.4, we show how the same variables can be expressed in other units, e.g., expressing yield per plant, per line or at the farm level.

8.2.1 Model Variables and Parameters

Model variables are defined in Table 8.1.

Intentionally, the model is kept as simple as possible, which makes it easily amenable for simulating different tropical seaweeds such as *Gracilaria*, *Kappaphycus alvarezii* (cottonii), and *Eucheuma denticulatum* (spinosum). The model has only 13 parameters, and for this study, we concentrate on cottonii, and carrageenan produced from it:

- Eight biochemical parameters ($rgmax$, $w_{f,max}$, m_f , m_{sd} , cf_{min} , cf_{max} , cfk , and cft_{50}), of which two are for growth ($rgmax$ and $w_{f,max}$), two are for converting from fresh weight to semidry weight (m_f and m_{sd}), and four are for calculating carrageenan concentration (cf_{min} , cf_{max} , cfk , and cft_{50}).
- Three economic parameters (FGP_c , PC_m , and PC_h).
- Two (farmer) decision parameters: hcl (harvest cycle length) and $w_{f,0}$ (replanting weight).

We present parameter estimates in Table 8.2. Additionally, in Table 8.2, we present parameters on farm

configuration (number of lines per farm, line length, line spacing, plants per meter line), which can be useful for unit conversion but which are not critically needed as input for the model.

8.2.2 Seaweed Growth Model

Seaweed growth formulae cited in this section are listed in Fig. 8.2.

Time (t) in the model is expressed in days after planting. For a year with multiple plantings, t can be calculated as shown in Eq. (1) (Fig. 8.2), where doy is the Julian day of the year, doy_0 is any planting day of the year, and hcl is the cycle length including the harvest day. The modulo— $mod()$ —is a standard mathematical operator that returns the remainder after division of one number by another. For example $mod(44,45) = 44$, $mod(45,45) = 0$, $mod(46,45) = 1$, $mod(47,45) = 2$, $mod(89,45) = 44$, $mod(90,45) = 0$, $mod(91,45) = 1$, etc. It generates a sawtooth timeseries in which t increases by 1 every day until reaching the harvest date (after 45 days), drops back to 0, and then increases again by 1 every day until reaching the next harvest date. For a simulation for a year, we will simulate from $doy = 1$ to 360 and we set $doy_0 = 1$.

We introduce a sigmoid biomass growth model (Fig. 8.3). Initially, the seaweed grows exponentially with a relative growth rate $rgmax$. Then, growth becomes almost linear, due to various factors such as self-shading, erosion, predation by herbivores, etc. Finally, growth flattens off to a maximum weight $w_{f,max}$. Equation (2) is the standard differential equation used in ecophysiological models for describing sigmoid growth.

From Eq. (2), we can derive Eq. (3), showing gross biomass (kg m^{-2}) at any point in time t (days after planting) for a given start weight $w_{f,0}$.

Of the harvested gross yield $w_{f,g}(t)$, one-part $w_{f,0}$ is “replanted” (the same day, to avoid desiccation), and the

Table 8.1 Variables of the Bio Economic Seaweed Model

Variable	Unit	Description
t	days	Days after planting
$w_{f,g}(t)$	kg FW m^{-2}	Gross biomass fresh from sea, at time t after planting
$w_{f,n}(t)$	kg FW m^{-2}	Net biomass fresh from sea, at time t after planting
$W_{f,n}(hcl, w_{f,0})$	kg FW $\text{m}^{-2} \text{ year}^{-1}$	Fresh (f) net (n) annual harvested biomass as a function of replanting weight $w_{f,0}$ and harvest cycle hcl
$W_{sd,n}(hcl, w_{f,0})$	kg SDW $\text{m}^{-2} \text{ year}^{-1}$	Semidried (sd) net (n) annual harvested biomass
$cf(t)$		Kilogram carrageenan per kilogram of semidry seaweed
$CAR(hcl, w_{f,0})$	kg $\text{m}^{-2} \text{ year}^{-1}$	Net annual harvested carrageenan
$FGP_{sd}(t)$	IDR kg^{-1} SDW	Farmgate price for semidry seaweed as a function of t , in Indonesian Rupiah
$I_g(hcl, w_{f,0})$	IDR $\text{m}^{-2} \text{ year}^{-1}$	Gross annual income per m^2
$PC(hcl)$	IDR $\text{m}^{-2} \text{ year}^{-1}$	Annual production cost per m^2
$I_n(hcl, w_{f,0})$	IDR $\text{m}^{-2} \text{ year}^{-1}$	Net annual farm income per m^2

Table 8.2 Parameter estimates for species *Kappaphycus alvarezii* (cottonii)

Parameters	Unit ^a	Value	BED ^b	Description	Source
rgr_{max}	$g\ g^{-1}\ day^{-1}$	0.06	B	Maximum relative growth rate	Range reported in literature for <i>K. alvarezii</i> : 0.05–0.08 (Periyasamy et al. 2019; Dawes et al. 1994)
$w_{f,max}$	$kg\ FW\ m^{-2}$	5.26	B	Maximum fresh weight	Figure 8.3, author's estimate. This value of $w_{f,max}$ gives for the set $rgr_{max} = 0.06$, $w_{f,0} = 0.15$, $hcl = 45$ the (farmer) reported 40 kg FW per line = 1.6 kg FW m^{-2} (with $L_l = 25$ and $L_w = 1.0$)
cf_{min}	$kg\ carrageenan\ kg^{-1}\ SDW$	0.234	B	Minimum chemical content at $t = -\infty$	Figure 8.2. Based on data in (Periyasamy and Rao 2017)
cf_{max}	$kg\ carrageenan\ kg^{-1}\ SDW$	0.374	B	Maximum chemical content at $t = +\infty$	Figure 8.2
cfk	day^{-1}	0.162	B	Steepness of slope with which content increases with days after planting	Figure 8.2
cf_{50}^i	day	34.7	B	Days after planting at which chemical content is halfway between cf_{min} and cf_{max}	Figure 8.2
m_f	$g\ g^{-1}$	0.90	B	Moisture content fresh from sea	Authors' interviews ^c
m_{sd}	$g\ g^{-1}$	0.343	B	Moisture content semidried (dried on platform on the beach by farmer)	Authors' interviews ^c
$w_{f,0}$	$kg\ FW\ m^{-2}$	0.15	D	Fresh biomass weight replanted	I. Neish pers. comm. (2021): 20–40 g/plant. Authors' calculation: 30 g/plant, with $PD = 5$ plants m^{-1} , line spacing $L_w = 1.0\ m \rightarrow 0.001 * 30 * 5 / (1.0) = 0.15$
hcl	days	45	D	Harvest cycle length: days from planting to harvesting, including the harvest day	Authors' interviews ^c
FGP_c	IDR kg^{-1} carrageenan	65,341	E	Farmgate price carrageenan	Authors' interviews. Normal farmgate price in 2019 was 23,000 IDR kg^{-1} SDW. According to Eq. 10 in Fig. 8.2, carrageenan content at normal harvesting time (45d) is 0.343, thus $FGP_c = FGP_{sd}(45)/cf(45) = 23,000/0.352 = 65,341$
PC_m	IDR m^{-2} day^{-1}	0.99	E	Production cost for maintenance (m). This includes depreciation of material plus daily maintenance of lines in sea	Authors' estimate based on (Tahang et al. 2019). Tahang et al. report "fixed costs" of in total 2,700,000 IDR $farm^{-1}\ year^{-1}$. Assuming a farm with 300 lines of 25 m at 1 m spacing we obtain $2,700,000 / (300 * 25 * 1.0) / 365 = 0.99$. Note highly uncertain!
PC_h	IDR m^{-2} $cycle^{-1}$	580	E	Production cost at harvesting (h). This is the sum of costs of harvesting + drying + replanting	Authors' estimate based on (Tahang et al. 2019). Tahang et al. report "variable costs" of in total 21,750,000 IDR $farm^{-1}\ year^{-1}$ and they report farmer harvesting 5× per year. Assuming a farm with 300 lines of 25 m at 1 m spacing, we obtain $21,750,000 / (300 * 25 * 1.0) / 5 = 580$. Note highly uncertain!
L_N		300	E	Number of lines per farm	Authors' interviews ^c . Range 200–1000
L_l	m	25	E	Length of a line	Authors' observations ^c . Standard rope length
L_w	m	1	E	Width = spacing = distance between lines	Authors' observations ^c
L_{pd}	Plants m^{-1}	5		Plant density, number of plants per meter	Authors' observations ^c

^a In the units, FW indicates fresh weight, SDW is semidry weight (dried on beach), and IDR is Indonesian rupiah

^b BED: parameter types—B, biochemical; E, economic; D, decision

^c Authors interviewed five farmers plus five traders in Sept 2019 in South West Sulawesi. Two of the authors are permanently based in South West Sulawesi

remaining part $w_{f,s}(t) - w_{f,0}$ is sold (after drying). Net fresh biomass production is therefore as shown in Eq. (4).

A number of growing cycles can be completed in 1 year. For simplicity, we will consider a year consisting of 360 days, and we will consider growing periods that give a

round number of cycles. For example, harvest cycles of $hcl = 30$ and 45 days gives a round number of 12 and 8 cycles. Thus, we can compare cultivation systems over the same total period of 360 days. The annual number of cycles is $N_h = 360/hcl$ (Eq. 5).

- ① $t = \text{mod}(\text{doy} - \text{doy}_0, \text{hcl})$
- ② $\frac{dw_{f,g}}{dt} = rgrmax * w_{f,g} * \left(1 - \frac{w_{f,g}}{w_{f,max}}\right)$
- ③ $w_{f,g}(t) = \frac{w_{f,max}}{1 + \left(\frac{w_{f,max} - w_{f,0}}{w_{f,0}}\right) * e^{-rgrmax * t}}$
- ④ $w_{f,n}(t) = w_{f,g}(t) - w_{f,0}$
- ⑤ $N_h = 360/\text{hcl}$
- ⑥ $lgp = \text{hcl} - 1$
- ⑦ $W_{f,n}(\text{hcl}, w_{f,0}) = N_h * w_{f,n}(lgp, w_{f,0})$
- ⑧ $W_{f,n}(\text{hcl}, w_{f,0}) = \left(\frac{360}{\text{hcl}}\right) * \left(\left(\frac{w_{f,max}}{1 + \left(\frac{w_{f,max} - w_{f,0}}{w_{f,0}}\right) * e^{-rgrmax * (\text{hcl} - 1)}}\right) - w_{f,0}\right)$
- ⑨ $W_{sd,n}(\text{hcl}, w_{f,0}) = \left(\frac{1 - m_f}{1 - m_{sd}}\right) W_{f,n}(\text{hcl}, w_{f,0})$
- ⑩ $cf(t) = cf_{min} + \frac{cf_{max} - cf_{min}}{1 + e^{-cfk(t - cft_{50})}}$
- ⑪ $CAR(\text{hcl}, w_{f,0}) = cf(\text{hcl}) * W_{n,sd}(\text{hcl}, w_{f,0})$

Fig. 8.2 Seaweed growth formulae cited in Sect. 8.2.2

Total net annual production can now be expressed as the annual number of harvests N_h times net biomass harvested per individual cycle. However, note that at the day of harvesting, the seaweed is harvested in the morning, sorted and replanted. Thus, in each cycle, 1 day is “lost,” i.e., the seaweed is not growing while not in the sea. With cycles of $\text{hcl} = 45$ days, there are eight harvests per year. The seaweed is growing in the sea for $8 * lgp = 8 (\text{hcl} - 1) = 8 * (45 - 1) = 352$ days, and it is on land for sorting for 8 days. Although it matters little for annual production, a theoretically correct statement is that the gross yield at harvesting is

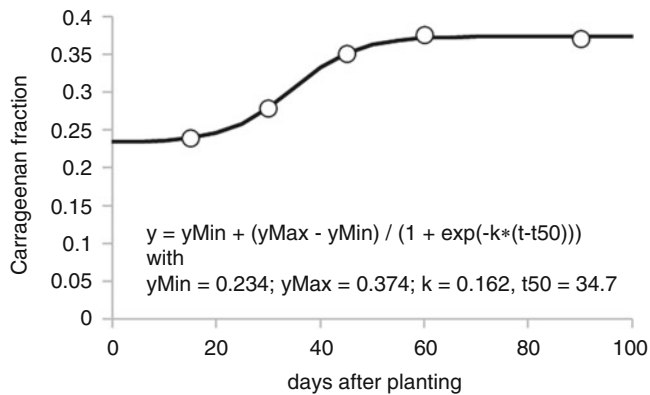


Fig. 8.3 Sigmoid function of carrageenan fraction in *Kappaphycus* as a function of plant age, fitted on data reported in (Periyasamy and Rao 2017)

not $w_{f,g}(\text{hcl})$ but $w_{f,g}(\text{hcl} - 1)$. We define the length of the actual growing period lgp as $lgp = \text{hcl} - 1$ per Eq. (6).

Annual net fresh yield is calculated from the number of harvests and the net yield at harvesting per Eq. (7). We use a lower case “w” in Eq. (4) for biomass weight at time t and an uppercase “W” in Eq. (7) for annual total biomass.

Combining the above equations, we can express net annual fresh production $W_{f,n}$ as a function of the four parameters hcl , $w_{f,0}$, $rgrmax$, and $w_{f,max}$ as shown in Eq. (8).

After harvesting, the seaweed is dried on platforms on the beach. Annual net semidry weight $W_{sd,n}$ (kg m^{-2}) is calculated from moisture contents of the seaweed fresh from sea (m_f) and semidry (m_{sd}), i.e., after drying on platforms on the beach (Eq. 9).

Typical values for the moisture content fresh from sea (m_f) for the seaweed *Kappaphycus alvarezii* (cottonii) are $m_f = 0.9$ and for the moisture content after drying on the beach: $m_{sd} = 0.35$ (35% moisture content after drying; farmer’s indication). The conversion factor for calculating semidry weight from fresh weight is then as follows: $((1 - m_f)/(1 - m_{sd})) = 0.15$. For example, a harvest of 40 kg FW (Fresh weight) will contain $0.9 * 40 = 36$ kg water and $(1 - 0.9) * 40 = 4$ kg dry matter. After drying to $m_{sd} = 0.35$, the semidry weight is $0.15 * 40 = 6.15$ kg SDW, of which 2.15 kg water and 4 kg dry matter. Check: $2.15/6.15 = 0.35$.

Next, we calculate the carrageenan content, which is in most *Kappaphycus/Eucheuma* research expressed as kg carrageenan per kg semidry weight. Periyasamy et al. (2019) showed carrageenan content increases with plant age. From the data reported in (Periyasamy and Rao 2017), we fit the sigmoid function shown per Eq. (10).

This sigmoid function ranges from cf_{min} at $t = -\infty$ to cf_{max} at $t = \infty$; parameter cfk determines the steepness of the slope, and cft_{50} is the time (in days after planting). At 45 days after planting $cf(45) = 0.352$. The seaweed *Eucheuma denticulatum* (spinosum) has a lower carrageenan content than *Kappaphycus*. To make the same equation work for *Eucheuma*, probably the only thing we would need to do is replace the parameters of the $cf(t)$ Eq. (11) to one that predicts lower $cf(t)$ for *Eucheuma* than for *Kappaphycus*.

Net annual carrageenan production, which is what ultimately industry will extract from the semidried seaweed collected from farms, can be written as per Eq. (11).

The much-used exponential model (Dawes et al. 1993, 1994; Kasim et al. 2016; Periyasamy et al. 2019; Setyawidati et al. 2017; Hurtado et al. 2001) simulates seaweed biomass with one parameter, the relative growth rate. Here, we introduced a new (sigmoid) model with only two parameters, $rgrmax$ and $w_{f,max}$, thus still simple. The second novelty of the model presented here is that we simulate multiple harvests in a cultivation system with replanting. Annual production depends on two (farmers’) decision parameters hcl and $w_{f,0}$. In its simplest form of simulating fresh biomass

that is all we need. We further added to the model two parameters mf and msd for converting fresh biomass to semidry biomass. And we added four parameters, cf_{min} , cf_{max} , cfk , and cft_{50} , for calculating the concentration of the chemical of interest; in the case of the seaweed *Kappaphycus*, we calculate the concentration of the chemical carrageenan.

8.2.3 Economic Model

Economic model formulae cited in this section are listed in Fig. 8.4.

Our interviews suggested that farmers receive a lower price per kg semi-dry seaweed when they harvested earlier than normal. This is consistent with Fig. 8.3, which shows lower carrageenan content for earlier harvest dates. In BESeM, farmgate price is calculated per Eq. (12) (Fig. 8.4), where FGP_c is a constant price per kg carrageenan. Table 8.2 shows how we estimated this parameter. Filling in $FGP_c = 65,341$ and the normal harvest cycle length of 45 days, we obtain $FGP_{sd}(45) = 65,341 * 0.352 = 23,000$ IDR kg^{-1} semidry; that was the normal price in 2019 (pre-COVID). Harvesting at, for example, 30 days, with carrageenan content $cf(30) = 0.279$ (Fig. 8.3), would result in $FGP_{sd}(30) = 65,341 * 0.279 = 18,230$ IDR kg^{-1} semidry.

Gross annual income I_g (IDR $m^{-2} year^{-1}$) is calculated per Eq. (13) (Fig. 8.4).

Combining Eqs. (10)–(13), we can also write gross income as a function of carrageenan production per Eq. (14) (Fig. 8.4).

Net income is calculated as gross income minus production costs. Production costs consist of two types of costs:

PC_m = “maintenance” costs, which include material depreciation (ropes, wood, boat, nets) and labor costs (checking growth while lines are in the sea, shaking the lines to get rid of epiphytes and sediment). We refer to these costs as maintenance (m) costs and express them in IDR per m^2 per day, since they occur on a continuous daily basis.

PC_h = “harvest” costs, which is the costs that occur only at the event of harvesting. This includes the full package of labor costs that occur from harvesting to replanting:

harvesting, drying, tying vegetative parts to new lines for replanting, and placing the new lines back into the sea. We refer to these costs as harvest (h) costs and express them in IDR per m^2 per cycle, since they occur at the end of each cycle.

Total production costs $PC(hcl)$ (IDR $m^{-2} year^{-1}$) summed over a period of 360 days for a seaweed farm can then be calculated per Eq. (15) (Fig. 8.4),

Where N_h is the number of harvests (Eq. 5, Fig. 8.2). We can see that a shorter harvest cycle (hcl) = more frequent harvesting (N_h) increases total costs through the right term $N_h * PC_h$.

Finally, net income I_n , expressed in IDR $m^{-2} year^{-1}$, is calculated per Eq. (16) (Fig. 8.4).

8.2.4 Unit Conversions

The BESeM expresses biomass in kg per square meter and profits in IDR m^{-2} per year. Expressing yields and profits per square meter is a scientific standardized method of reporting. Reporting in a standardized way (i.e., per m^2 per year) allows for objective comparisons of productivity of farms of different size or for comparisons between cases where plant density, standard line length, or line spacing is different from the values considered. The conversion from kg m^{-2} tot kg per line, gram per plant, or Indonesian rupiah per farm is straightforward and is illustrated below:

- The cultivation area for a line of length $L_l = 25$ m placed in parallel with $L_w = 1.0$ m between the lines is $L_l * L_w = 25 * 1.0 = 25$ m^2 .
- A biomass of 40 kg/line thus corresponds with $40/25 = 1.6$ $kg m^{-2}$.
- Or the other way round: a simulated biomass of 2.0 $kg m^{-2}$ corresponds with $2.0 * L_l * L_w = 50$ $kg line^{-1}$.

Conversion from $kg m^{-2}$ to gram plant $^{-1}$ is equally straightforward:

- If plants are spaced at 20 cm, then plant density on the line is $L_{pd} = 1.0/0.20 = 5$ plants m^{-1} .
- Plant density per square meter is $PD = L_{pd}/L_w$. At $L_{pd} = 5$ and parallel lines at 0.8 m, spacing between the lines is $L_w = 0.8$, $PD = 5/0.8 = 6.25$ plants m^{-2} . At a line spacing of $L_w = 1.0$ m, PD is $5/1.0 = 5$ plants m^{-2} .
- Conversion from plant weight w $kg m^{-2}$ to plant weight y in gram per plant is $y = 1000 * w/PD = 1000 * w/(L_{pd}/L_w)$ and, the other way round, $w = 0.001 * y * PD$. For the L_{pd} and L_w values in Table 8.2, a plant weight of 30 gram

$$(12) \quad FGP_{sd}(t) = FGP_c * cf(t)$$

$$(13) \quad I_g(hcl, w_{f,0}) = W_{n,sd}(hcl, w_{f,0}) * FGP_{sd}(hcl)$$

$$(14) \quad I_g(hcl, w_{f,0}) = CAR(hcl, w_{f,0}) * FGP_c$$

$$(15) \quad PC(hcl) = 360 * \left(PC_m + \frac{1}{hcl} * PC_h \right) = 360 * PC_m + N_h * PC_h$$

$$(16) \quad I_n(hcl, w_{f,0}) = I_g(hcl, w_{f,0}) - PC(hcl)$$

Fig. 8.4 Economic model formulae cited in Sect. 8.2.3

per plant thus corresponds with $w = 0.001 * 30/(5/1.0) = 0.15 \text{ kg m}^{-2}$

Conversion from Indonesian rupiah per square meter per year ($\text{IDR m}^{-2} \text{ year}^{-1}$) to farm level ($\text{IDR farm}^{-1} \text{ year}^{-1}$) is by multiplying with farm area A (m^2):

- Farm size in square meters can be calculated from the number of lines that a farmer has (L_N), the length of lines (L_l), and the spacing between lines (L_w). For a farm with $L_N = 300$ lines, farm area A (m^2) can be calculated as $A = L_N * L_l * L_w = 300 * 25 * 1.0 = 7500 \text{ m}^2$ ($=0.75 \text{ ha}$).
- A net profit of $I_n = 40,000 \text{ IDR m}^{-2} \text{ year}^{-1}$ then corresponds with $I_n * A = 40,000 * 7500 = 300 \text{ million IDR}$ per farm per year.
- If the family household consists of four family members working in the seaweed enterprise, then income per head can be calculated by dividing the farm income by 4.

8.3 Model Illustration

8.3.1 Parameter Estimation

8.3.1.1 Biochemical Parameters

Farmers in a number of sites in South West Sulawesi (visited by the authors in 2019 and 2020) reported gross harvests of 40 kg FW per line, with a harvest cycle of hcl 45 days and a standard line length of $L_l = 25 \text{ m}$, at $L_w = 1.0 \text{ meter}$ spacing. Farmers gross yield is thus $40/(1*25) = 1.6 \text{ kg FW m}^{-2}$, and yield per plant at 45 dap is 320 gram fresh per plant (at 5 plants per m). Iain Neish (pers. comm., 2021) reported farmers' common practice replanting weights of 20–40 g. We observed similar values during our visits, but also quite large variation in farmers' response to our questions on planting density and planting weight. Assuming an average of 30 g plant^{-1} , this corresponds with $30/1000*125 = 3.7 \text{ kg FW line}^{-1}$ and $0.15 \text{ kg FW m}^{-2}$. Parameter $rgrmax = 0.06$ was estimated from the literature (Table 8.2). With this, three out of four biological parameters ($rgrmax = 0.06$, $hcl = 45$ and $w_{f,0} = 0.15$) were known. The remaining unknown parameter $w_{f,max}$ was estimated, such that simulated $w_{f,g}(t = 45)$ (Eq. 3) equaled the observed gross yield at harvesting (1.6 kg FW m^{-2}). Figure 8.5 illustrates how we estimated $w_{f,max}$ on this minimal calibration set. Clearly, the only way to check if our estimate of $w_{f,max}$ is correct, one would have to monitor growth for a longer time than the common 45 days or less. Figure 8.5 also shows in the gray line the exponential model with infinite growth. Early growth is exponential, but we can see the exponential model overestimates biomass in later stages after planting (Fig. 8.5).

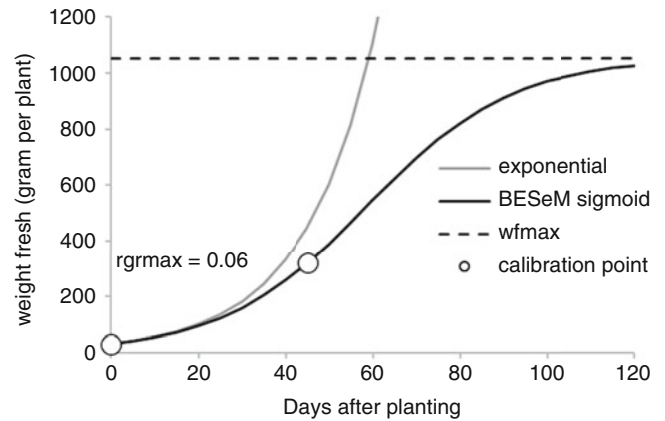


Fig. 8.5 Estimation of $w_{f,max}$ and illustration of the exponential and sigmoid model

8.3.1.2 Economic Parameters

At least for the biological parameters, we can estimate them through experiments. Economic parameters are the farmgate price FGP_c and the production costs PC_m (“maintenance” costs) and PC_h (“harvest” costs). Farmgate prices are subject to economics of price and demand. Tourism in Indonesia has collapsed since the ongoing COVID-19 pandemic. Part of the people working in the tourism sector losing their jobs have moved into seaweed farming. This has led to increased supply, which has in turn had a negative effect on farmgate prices. According to Kosperindo staff in Makassar Indonesia, farmgate prices have recently dropped from 22,000–24,000 IDR kg^{-1} semidry in 2019 to 13,000–14,500 IDR kg^{-1} semidry in 2021. Kosperindo is a seaweed farmers' cooperative in Sulawesi. See also Langford (Langford et al. 2021) for effects of COVID-19 on cultivated area and prices.

Production costs PC_m are aggregate values, consisting of depreciation of ropes, wooden poles, plastic bottles, boats, and more. We estimated this parameter based on Tahang et al. (2019); see Table 8.2. A major source of uncertainty is that (Tahang et al. 2019) did not report farm size, while we express production costs in IDR per m^2 . In our calculation of PC_m from Tahang's data, we assumed a farm size of $L_N = 300$ lines. Other sources of uncertainty are in the estimates of depreciation costs. For example, the number of years to replacement will depend on the quality of the material (boat, line, etc.), and how it is handled by the seaweed farmer. Replacement time may vary markedly. Also, prices at which material is bought will vary from time to time and from site to site.

Harvest costs PC_h are aggregate values, consisting of harvesting (normally done by the men), tying seaweed cuttings to new ropes (normally done by the women) and planting out the lines back into the sea (normally done by the men). We estimated this parameter based on Tahang et al.

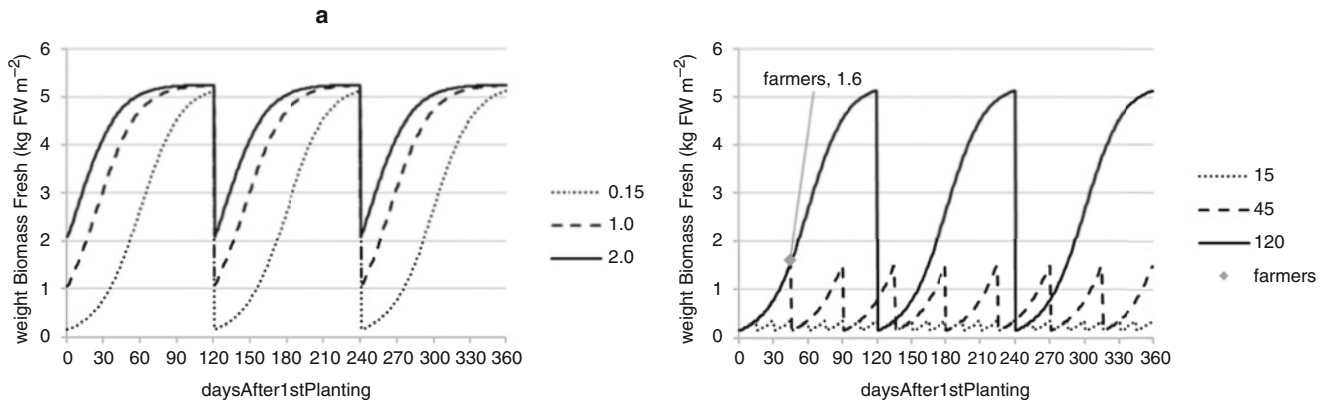


Fig. 8.6 Growth cycles for farming systems harvesting every $hcl = 15, 45,$ and 90 days. **(a)** Fresh biomass for a harvest cycle length of $hcl = 120$ days, at three initial plant weights ($w_{f,0} = [0.15, 1.0, 2.0]$

kg FW m^{-2}); **(b)** fresh biomass (kg FW m^{-2}) with 3 harvest cycle lengths ($hcl = [15, 45, 120]$ days) at replanting weight $0.15 \text{ kg FW m}^{-2}$

(2019) (Table 8.2). Smaller farms will rely entirely on family labor; larger farms will also hire wage labor for the tying up of new ropes. The difficulty in estimating these labor costs is that seaweed is mainly a family business in which family members do not pay each other for their services. At best, these costs could be estimated from wages of laborers. The COVID-19 pandemic has led to increased unemployment in Indonesia, with a negative effect on wages. One may expect current PC_h to be lower than our (pre-COVID) estimate in Table 8.2. Both our farmgate price and the production costs are today probably lower than before COVID. Lower farmgate prices may partially cancel out against lower production costs, still leading to more or less realistic estimates of net income.

Evidently, our parameter estimates are quite uncertain. The following sections should be considered more as illustrations of the model than as predictions of the true values.

8.3.2 Harvest Cycles

Figure 8.6a shows three sigmoid curves for three different replanting weights. With a low replanting weight of $0.15 \text{ kg FW m}^{-2}$ (farmers' practice), growth is initially exponential, changing to linear and then slowing down to the plateau of $w_{f,max}$. With this low replanting weight, the plateau of around 5 kg FW m^{-2} is reached only at approximately 120 days. A high replanting weight of 2.0 kg FW m^{-2} gives much stronger initial growth. Then the plateau of 5 kg FW m^{-2} is reached already at around 60 days. Figure 8.6b shows three cycles, of 15, 45, and 120 days, respectively. A short cycle of 15 days gives more (24) cycles per year but lower net yield at harvesting ($0.33 \text{ kg FW m}^{-2}$). A long cycle of 120 days gives less (three) cycles per year and higher net yield at harvesting ($5.12 \text{ kg FW m}^{-2}$).

8.3.3 Optimization

Farmers can influence their production and income through their decisions on replanting weight and harvest cycle length. As we will show below, the BESeM can be used to find the optimum replanting weight and optimum harvest cycle length. The BESeM was run $7 \times 7 = 49$ times, at seven different harvest cycle lengths ($hcl = [5, 15, 30, 45, 60, 90, 120]$ days) and seven different replanting weights ($w_{f,0} = [0.01, 0.05, 0.15, 0.5, 1.0, 2.0, 3.0]$ kg FW m^{-2}). Results are presented in Fig. 8.7. We discuss the results

1. Figure 8.7a shows gross yields per harvest cycle. At a start weight of $30 \text{ g/plant} = 0.15 \text{ kg FW m}^{-2}$ and for a cycle of 45 days, gross yield of 1.5 kg FW m^{-2} (Fig. 8.7a) corresponds with the gross yield of 1.6 kg FW m^{-2} shown in Fig. 8.6 (the difference between 1.6 in Fig. 8.6 and 1.5 in Fig. 8.7a is due to rounding).
2. Figure 8.7c shows net yield calculated as the gross yield minus the replanted weight. At $w_{f,0} = 0.15$ with $hcl = 45$ days, $1.5 - 0.15 = 1.35 \text{ kg FW m}^{-2}$ is sold (Fig. 8.7c). At this particular combination of $w_{f,0}$ and hcl , the fraction sold is $1.35/1.5 = 0.90$ (90%) and is shown in Fig. 8.7b.
3. A long cycle gives the highest net fresh yield per cycle (Fig. 8.7c), but one has less harvests per year. Figure 8.7d, e show annual net yields. Annual net yields are highest with a combination of a high replanting weight ($2.0 \text{ kg FW m}^{-2} = 400 \text{ g plant}^{-1}$) and a short cycle of only 15 days. The pattern in Figs. 8.5d and 8.7e is exactly the same; the only difference is in the numbers, as we are applying a standard conversion (Eq. 9) from fresh weight to semi-dry weight.
4. When considering carrageenan production (Fig. 8.7f), the optimum shifts a bit toward longer cycles (45 days) and a medium replanting weight ($1.0 \text{ kg FW m}^{-2} = 200 \text{ g}$

- plant⁻¹), because according to Fig. 8.2 in our model, carrageenan concentration is lower shortly after planting.
- Gross income (Fig. 8.5g) follows the same pattern as carrageenan (Fig. 8.7f); the only difference is in the numbers, as we are applying a standard conversion (Eq. 15) from carrageenan yield to gross income.
 - Finally, for net income (Fig. 8.7h), optimum farm management is similar as for the gross income. In other simulations (not shown) with higher harvesting costs (PC_h), we did find net income was maximized with less frequent harvesting.

An important message from Fig. 8.7a–h is that it is really the combination of start weight and cycle length that matters. For example, Fig. 8.7g shows that, at a low replanting weight, it is better to go for a longer cycle and, with a high replanting weight, it is better to go for a shorter cycle. It does not make sense recommending an optimal cycle length without considering replanting weight. And it does not make sense recommending an optimum replanting weight without

considering cycle length. These two important farmers’ decisions should be made as “package.”

Table 8.3 presents a comparison of farmers’ practice with the optimum, which we derived in Fig. 8.7h. The table suggests farmers can increase their income by a factor 2.5 (from 31,997 to 79,925 IDR m⁻² year⁻¹ with a similar cycle (45 days) and a much higher replanting weight (200 instead of 30 g fresh plant⁻¹). They would be selling a smaller part of their harvest (75% instead of 90%). The smaller fraction sold is more than offset by the much higher growth obtained at greater replanting weight.

From Fig. 8.7, we can calculate gross farmers’ income per month as: 37.0 * 1000 IDR m⁻² year⁻¹ (Fig. 8.7g) * 7500 m² (farm size)/12 (months per year)/4 (people per family) = 5.8 M IDR head⁻¹ month⁻¹. This is about 2× the minimum wage of 3.2 mln IDR month⁻¹ in provincial South West Sulawesi. This seems a reasonable model outcome; it seems reasonable that a seaweed farmer would earn more than an average wage worker. And it seems reasonable a seaweed farmer would not earn many orders of magnitude more than the average wage worker, e.g., it would be strange if our model had predicted

Harvesting cycles of 5, 10, 15, ..., 90 days. Simulation of 360 days.

(Re) planting fresh weight			(a) Gross fresh yield (kg FW m ⁻² cycle ⁻¹)							(b) fraction of gross yield sold						
g plant ⁻¹	kg line ⁻¹	kg m ⁻²	5	15	30	45	60	90	120	5	15	30	45	60	90	120
2	0.25	0.01	0.0	0.0	0.1	0.1	0.3	1.4	3.6	0.21	0.56	0.81	0.92	0.97	0.99	1.00
10	1.25	0.05	0.1	0.1	0.3	0.6	1.2	3.4	4.8	0.21	0.55	0.81	0.91	0.96	0.99	0.99
30	3.75	0.15	0.2	0.3	0.7	1.5	2.6	4.5	5.1	0.20	0.54	0.79	0.90	0.94	0.97	0.97
100	12.5	0.5	0.6	1.0	1.9	3.1	4.1	5.0	5.2	0.19	0.51	0.74	0.84	0.88	0.90	0.90
200	25	1.0	1.2	1.8	3.0	4.0	4.7	5.2	5.2	0.17	0.46	0.67	0.75	0.79	0.81	0.81
400	50	2.0	2.3	3.1	4.1	4.7	5.0	5.2	5.3	0.13	0.35	0.51	0.58	0.60	0.62	0.62
600	75	3.0	3.3	4.0	4.7	5.0	5.2	5.2	5.3	0.09	0.25	0.36	0.40	0.42	0.43	0.43

(Re) planting fresh weight			(c) Net fresh yield (kg FW m ⁻² cycle ⁻¹)							(d) Net fresh yield (kg FW m ⁻² year ⁻¹)						
g plant ⁻¹	kg line ⁻¹	kg m ⁻²	5	15	30	45	60	90	120	5	15	30	45	60	90	120
2	0.25	0.01	0.0	0.0	0.0	0.1	0.3	1.3	3.5	0.2	0.3	0.5	0.9	1.7	5.4	10.6
10	1.25	0.05	0.0	0.1	0.2	0.5	1.2	3.3	4.8	0.9	1.5	2.5	4.3	7.0	13.4	14.4
30	3.75	0.15	0.0	0.2	0.6	1.3	2.4	4.3	5.0	2.7	4.3	6.9	10.6	14.5	17.4	14.9
100	12.5	0.5	0.1	0.5	1.4	2.6	3.6	4.5	4.7	8.4	12.4	17.2	20.7	21.6	18.1	14.2
200	25	1.0	0.2	0.8	2.0	3.0	3.7	4.2	4.2	14.8	20.1	23.9	24.2	22.1	16.6	12.7
400	50	2.0	0.3	1.1	2.1	2.7	3.0	3.2	3.3	21.8	26.1	25.2	21.8	18.2	12.9	9.8
600	75	3.0	0.3	1.0	1.7	2.0	2.2	2.2	2.3	21.9	23.5	19.9	16.0	12.9	9.0	6.8

(Re) planting fresh weight			(e) Net semidried yield (kg SDW m ⁻² year ⁻¹)							(f) Carrageenan yield (kg m ⁻² year ⁻¹)						
g plant ⁻¹	kg line ⁻¹	kg m ⁻²	5	15	30	45	60	90	120	5	15	30	45	60	90	120
2	0.25	0.01	0.0	0.0	0.1	0.1	0.3	0.8	1.6	0.01	0.01	0.02	0.05	0.10	0.31	0.61
10	1.25	0.05	0.1	0.2	0.4	0.7	1.1	2.1	2.2	0.03	0.05	0.11	0.23	0.40	0.77	0.83
30	3.75	0.15	0.4	0.7	1.1	1.6	2.2	2.7	2.3	0.10	0.16	0.29	0.57	0.83	1.00	0.86
100	12.5	0.5	1.3	1.9	2.6	3.2	3.3	2.8	2.2	0.30	0.45	0.72	1.11	1.23	1.04	0.82
200	25	1.0	2.3	3.1	3.7	3.7	3.4	2.6	2.0	0.53	0.74	1.01	1.30	1.26	0.96	0.73
400	50	2.0	3.4	4.0	3.9	3.4	2.8	2.0	1.5	0.79	0.96	1.06	1.17	1.04	0.74	0.56
600	75	3.0	3.4	3.6	3.1	2.5	2.0	1.4	1.0	0.79	0.86	0.84	0.86	0.74	0.52	0.39

(Re) planting fresh weight			(g) Gross Income (thousand IDR m ⁻² year ⁻¹)							(h) Net Income (thousand IDR m ⁻² year ⁻¹)						
g plant ⁻¹	kg line ⁻¹	kg m ⁻²	5	15	30	45	60	90	120	5	15	30	45	60	90	120
2	0.25	0.01	0.4	0.7	1.4	3.3	6.4	20.2	40.0	-41.7	-13.6	-5.9	-1.7	2.6	17.5	37.9
10	1.25	0.05	2.2	3.6	7.0	15.0	26.3	50.3	54.0	-39.9	-10.7	-0.4	10.0	22.4	47.6	51.9
30	3.75	0.15	6.5	10.3	19.0	37.0	54.0	65.3	56.1	-35.6	-4.0	11.7	32.0	50.1	62.6	54.0
100	12.5	0.5	19.8	29.6	47.3	72.7	80.7	68.2	53.3	-22.3	15.4	40.0	67.7	76.9	65.5	51.2
200	25	1.0	34.9	48.3	65.8	84.9	82.6	62.6	47.9	-7.2	34.0	58.5	79.9	78.8	59.9	45.8
400	50	2.0	51.5	62.6	69.3	76.4	68.0	48.5	36.7	9.4	48.3	62.0	71.4	64.1	45.8	34.6
600	75	3.0	51.8	56.3	54.8	56.2	48.3	33.7	25.5	9.7	42.0	47.5	51.2	44.4	31.1	23.4

Fig. 8.7 Scenarios of production and income as a function of replanting weight (rows) and harvest cycle length (columns)

Table 8.3 Comparison between simulated farmers' practice and simulated optimum

	Farmers' practice	Optimum	References
Net income (IDR m ⁻² year ⁻¹)	31,997	79,925	Figure 8.6h
Replanting fresh weight (kg FW m ⁻²)	0.15	1.0	Figure 8.6h
Replanting fresh weight (g plant ⁻¹)	30	200	Figure 8.6h
Harvest cycle length (days)	45	45	Figure 8.6h
Gross yield per harvest (kg FW m ⁻²)	1.5	4.0	Figure 8.6a
Gross yield per harvest (g plant ⁻¹)	294	806	Figure 8.6a
Fraction sold	90%	75%	Figure 8.6b
Fraction replanted	10%	25%	1—Fig. 8.6b

the seaweed farmer earning 10 or 100 times as much as the average wage worker.

8.4 Discussion

8.4.1 Scope for Improving Farm Income?

At the Phyconomy Coalition, online workshop July 7–8, 2021 (<https://www.phyconomy.org/tpcd1/>), Dr. Iain Neish responded to our presentation (van Oort et al. 2021) by stating “We did trials around Bantaeng and Bulukumba in the IFC-PENSA project (2004–2008) that showed much better return per unit cost/effort when bibit about 150–200 (or even as much as 500) g were used as starting material, compared to when small bibit about 20–40 g were used. Despite that, farmers persisted in using the very small bibit. The reason given, was that village ladies were paid on a piecework basis per planted line to attach bibit. Smaller bibit means more lines must be planted ... hence more income to the ladies. In fact, the size of harvested fronds in much of SulSel was smaller than the size of propagules typically planted around Zamboanga, Philippines.”

Our optimization (Fig. 8.7h, Table 8.3) suggests a similar optimum replanting weight (100–200 g plant⁻¹), quite a remarkable outcome considering that our model was developed independently of the work by Dr. Neish. Our calculations suggested farmers can more than double their income by adopting this alternative management. Should we conclude farmers have great scope for increasing their income?

A word of caution is needed here. During our visit to seaweed farms in South West Sulawesi, farmers reported replanting weights ranged between 50 and 100 g per plant. In one case where we actually weighed a cutting, we measured 10 g. If actual replanting weight is 100 g per plant instead of the 30 g used in Table 8.3), then for these farmers the estimated net income would be 67,683 instead of 31,997 M IDR m⁻² year⁻¹ (Fig. 8.7h), and thus for these 100 g farmers, there would be much less to gain toward the simulated maximum of 79,925 M IDR m⁻² year⁻¹. We should note here there has been little published research on

actual farmers' practice. This one caution against claiming high potential income gains. A second word of caution has to do with model uncertainty. Reality is more complex than captured here in our model, since a model is always a simplification of reality. In reality, farmers may need fast cash to repay loans and pay school fees, etc. This may lead them to opt for shorter cycles and sell a large percentage of their harvest (which as we have shown can lead to lower net income). A third caution is that it is easy to simulate high yields on our computer but much harder to achieve them in practice. Sometimes for various reasons, *Kappaphycus* simply will not grow at a specific geographical site. In that case, farmers opt for more robust seaweeds like *Gracilaria* or *Eucheuma denticulatum* (spinosum) for which farmgate prices are much lower and thus also income generated is lower. We might find income for the *Eucheuma* farmer is about 50% lower (compared with *Kappaphycus*), but this would apply both to the farmers' common practice and our optimized management. It does not necessarily change our conclusion that higher replanting weights generate more income.

This being said, the logic of our model seems to be clear and our model results do seem to be in agreement with previous experience quoted above. In the very least, it calls for more experimentation. Our model outcomes can be considered hypotheses which are easily enough tested in the field (or actually in the sea), simply by planting seaweed at different starting weights and monitoring its growth.

8.4.2 Effects of the Environment

The reader will have noted environmental effects, such as effects of nutrient concentrations, temperature, irradiance, turbidity, etc., are not incorporated in our biological model. We briefly discuss how such effects could be incorporated.

8.4.2.1 Temperature, Irradiance, Nutrients

Implicitly, our biological parameters rg_{max} and wf_{max} are determined by the environment. Other sites with different environments will have different rg_{max} and wf_{max} than those in Table 8.2, which were estimated for a specific site in

this study. One may expect higher values for rg_{max} and $w_{f,max}$ in more favorable environments. Consider spatial and temporal variation in environmental variables. More complex models are needed when environmental variables fluctuate strongly during the year. In temperate climates temperature and irradiance are low during winter and high during summer. In comparison, tropical climates have fairly constant temperature and irradiance throughout the year, which makes it less urgent to incorporate temporal variation into a tropical seaweed cultivation model. Light can be a limiting factor if cultivation is from seaweed growing upward from a deep seafloor. Light is hardly a limiting factor in tropical cultivation systems with seaweed cultivated on lines or in nets near the surface. Regardless of climate, nutrient concentrations are often higher near river mouths (which flush nutrients into the sea). Higher rg_{max} and $w_{f,max}$ values may therefore be expected near river mouths. It is possible to determine from experiments functions of $w_{f,max}(X)$, i.e., $w_{f,max}$ as function of environmental variable X ; for example, X could be phosphate (PO_4^{3-}) concentration. As a starting point of elaborating the BESem with environmental effects, we propose to focus more on modeling spatial variation in rg_{max} and $w_{f,max}$ in relation to spatial variation in environmental conditions and less on temporal fluctuations. It requires experiments with simultaneous monitoring of environmental conditions and biomass. We found no such studies in the literature. Clearly there is a need for further experimental research in this domain.

8.4.2.2 Monsoon

According to farmers interviewed, in South West Sulawesi, the December–January–February–March part of the year is unsuitable for seaweed cultivation because the sea is too rough during that (monsoon) time. Rather than explicitly modeling lower production during this period, we could simply limit our simulations to the shorter 8 months period that is suitable for cultivation. During this new reference period of now 8 months $(8/12)*360 = 240$ days, farmers can complete 8 cycles of 30 days, 5 cycles of 45 days, or 4 cycles of 60 days. Instead of calculating aggregate yields over a full year, carrageenan production and income would now be calculated over this period of 240 days. It would not fundamentally change our approach. For the incomes reported in Fig. 8.7, these could all be multiplied with $(8/12)$, and we would still find income is maximized at the same combination of $w_{f,0} = 200$ gram per plant and $h_{cl} = 45$ days.

8.4.3 Uncertainties, Need for Further Research

We already reflected on some of the uncertainties in our parameter estimates. The difficulty of estimating $w_{f,max}$ with

limited data from interviews shows how very little is needed to make a first rough estimate of this parameter (Fig. 8.3). At the same time, it shows that without any observations closer to $w_{f,max}$ our estimate of $w_{f,max}$ remains very uncertain. Many of the parameters estimates listed in Table 8.2 are based on limited personal observation. For the biological parameters, we observed in the literature a general lack of experimentation, where growth was monitored longer than 45 days (see references quoted in the introduction). We hypothesized a sigmoid model. Although it is a biologically plausible model, to date there is not a single empirical tropical seaweed study that can confirm whether growth is indeed sigmoid. Perhaps future experiments will reveal biomass decreases again after certain time, due to processes of, e.g., herbivory. This remains to be tested. With lack of such longer time experiments, we had to improvise to estimate a key parameter, $w_{f,max}$, which can only really be determined from experiments, where growth is monitored for a longer period than 45 days. We also found no published studies where in the same growing environments growth was monitored for species planted at different initial plant weights, while our model suggests clear and strong effects of initial plant weights. There is a clear need for experiments in which growth is monitored for a longer period of time and experiments on effect of initial plant weight.

There is also much uncertainty about the economic parameters. Two studies provide the quantitative data we need (Tahang et al. 2019; Limi et al. 2018). One particular issue is that in BESem economic production cost parameters are expressed in IDR square meter ($IDR\ m^{-2}$) while these two studies report production at the farm level without reporting farm size. A second issue is that our economic parameters were determined during pre-COVID-19 times. The COVID-19 pandemic seemed to drive many people into seaweed farming, leading to more and cheaper wage workers but also larger production volumes which in turn lead to reduced farmgate prices. Over time, it may be necessary to reestimate the economic parameters of the model.

8.5 Conclusions

A simple model was presented for simulating production and economics of tropical seaweed cultivation. The model has a limited number of parameters, which makes it easily amenable to other seaweeds and other sites. Parameter estimates were presented, and uncertainties in parameter estimation were discussed. A simulation example suggests farmers can increase income by using cuttings with a higher weight than they are currently using. A literature review suggests still much need for further experimentation.

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