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# A Pareto Multi-Objective Optimisation for Sustainable Expansion in Sago Plantations

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Sago palm is an emerging crop for starch production which is predominately found in southeast Asia. Its expansion has potential danger to ecologically sensitive terrestrial ecosystems. This work aims to provide expansion strategies for sustainable sago plantation expansion based on the increase in sago starch demand. Mathematical optimisation model of the class linear programming is developed. The total land area available for expansion under the different land types is considered. The developed model determines the optimised area under each land type to be used for sago plantation expansion based on the trade-off between expansion cost and carbon emissions. $\varepsilon$-constraint method is used in solving the multi-objective problem. Unlike the other methods, $\varepsilon$-constraint enables to generate a range of optimal solutions. A case study with different land use types - disturbed tropical forest, disturbed peatland and swampy shrubland were considered to demonstrate the proposed model. Pareto frontier is presented between expansion cost and carbon emission using $\varepsilon$ constraint method, providing a range of expansion strategies to the decision maker. The results show that the annualised expansion cost and the annual carbon emission that is inevitable to meet the expected demand is 1.15 M USD and 4.25 t $CO_2$-eq/ha/y.

## 1. Introduction

Sago palm is native to southeast Asia and is found as wild trees in swampy forests. It is largely found in Papua New Guinea, Indonesia, and Malaysia as well as in small parts of Thailand and Philippines. Sago starch is produced from sago palm and is seen as a potential alternative to conventional starch sources like corn, sweet potato, cassava, etc. Unlike the conventional crops, sago starch is derived from the trunk of sago palm and has a very high yield of 20 -30 t/ha/y (Amin et al., 2019). Sago palm is also a very versatile crop in terms of its agro-climatic requirements and product properties, with applications in food and non-food industries. Despite its potential, sago remained an underutilised crop for starch production. This is mainly because of well-established agronomical practices used for crops like corn, cassava, etc. which made the cultivation easier for the farmers. Also, high maturity period of about 9 y – 12 y required by sago palms led to its neglect. However, with increasing demand for starch and preference of sago starch for certain niche applications, has pushed its demand in the past decade. Seizing this opportunity, countries like Malaysia and Indonesia have shown intent in developing sago plantation estates (Mohamad et al., 2016). In this circumstance, the expansions in sago plantations require a cautious approach. Southeast Asia is a region of rich ecosystems (such as tropical forests and peatlands) with high ecological value. An unplanned expansion is more likely to result in land use changes (LUC) that have disproportionate environmental impacts to their economic benefits.

The above discussion argues for the need to plan expansions in sago plantations. Typically, an estate company would prefer to invest less cost in expansion to achieve higher gain. However, less cost may come with high environmental impact. It involves additional cost to choose a more sustainable alternative. For example, swampy grassland has higher carbon footprint compared to shrubland though the land clearing cost is lesser (Agus et al., 2013). Similarly, degraded peatland result in higher carbon emission compared to

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degraded tropical forest but requires less cost (Agus et al., 2013). Evidently, expansion cost and carbon emission are conflicting objectives that are to be accounted while planning for sustainable plantation expansion. In order to address these conflicting objectives, multi-objective optimisation is required.

Wan et al. (2016) developed an optimisation model to synthesise sustainable pathways of sago value chain for the prevailing sago starch demand. However, the work has not considered optimising expansions that may be needed in the value chain to meet any increase in future demand. Previous works on sustainability in sago value chain were focused on waste management (Ho et al., 2019), water treatment (Ho et al., 2019) and integrated biorefinery (Wan et al., 2016). The fundamental unit of sago value chain is the sago plantations, but very limited works have addressed sustainability issues at plantations. A generic mathematical model for optimisation of expansions in agrarian lands to reduce tropical deforestation is developed (Rajakal et al., 2019) This has also been extended to sago plantation where expansion cost and carbon penalty cost are considered (Rajakal et al., 2020). However, these works were restricted to only forest lands with an objective to minimise LUC of forest lands and does not account other land types. Also, they account for only emissions due to biomass degradation and does not consider emissions due to soil decomposition. Besides, fixed area of land parcels that are available for expansion are taken as parameters and the models make optimised selection of land based on minimal cost. The literature survey has led to identify the following research gaps:

- High focus exclusively on forest lands, which does not apply for other land types.
- Emissions due to soil decomposition is not considered.
- Limitations in providing comprehensive LUC strategy at a macro level.

The current work aims to address the research gaps by considers the different land types suitable for sago plantation development in optimising sustainable sago plantation expansion. Also, the emissions both from biomass degradation and soil decomposition is accounted in this work. The total land area of the different land use types is pooled and this work aims to provide expansion strategies by determining the optimised area under each land type to be used for sago plantation expansion based on the trade-off between expansion cost and carbon emissions. This forms a multi-objective optimisation problem. One of the simpler and effective way of solving these problems, especially if it involves only bi-objectives, is $\varepsilon$-constraint method. It is widely used for optimising trade-offs amongst in multi-objective problems like biodiesel supply chain (Orjuela-Castro et al., 2019), mushroom supply chain (Shishebor and Zare, 2019), logistics in agro industry (Ramezani and Naderi, 2018), and food supply chain (Rohmer et al., 2019).

The rest of the paper is organized as follows - A detailed problem definition is presented in Section 2. The mathematical formulations developed for optimising the area under each land type is presented in Section 3. To illustrate the developed model, a case study is solved in Section 4 followed by results and discussion in Section 5. Finally, conclusion and contributions of this research is presented in Section 6.

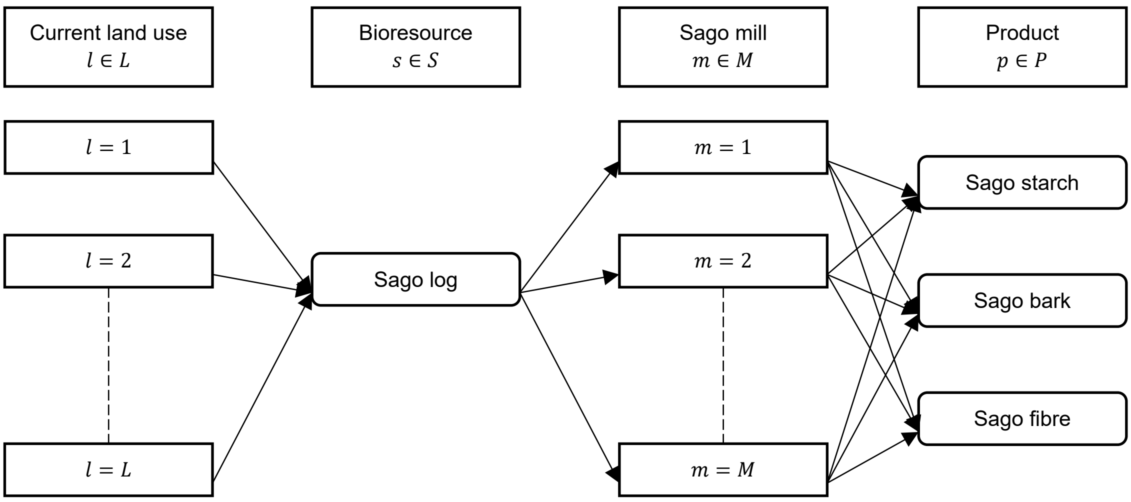


*Figure 1: Generic superstructure of sago value chain*

## 2. Problem definition

Figure 1 presents a typical sago value chain. It consists a set of land types $l \in L$ that are categorised based on their current land use. The maximum available area of land type $l \in L$ during the period *t*, $A_{l,t}^{Max}$ (ha) is surveyed and provided to the model. Sago log is the primary product of interest that is harvested from sago plantations. The sago logs are then transported to the sago mills $m \in M$. At the mill, the sago logs are processed to produce products $p \in P$, where sago starch is the primary product. The current work aims to determine the optimised area of land, $A_{l,t}^{PL}$ (ha) to be used for sustainable sago plantation expansion to meet the product (sago starch) demand, $D_{p,t}^{Product}$during the period *t.* The optimised area is determined by trade-off between expansion cost and carbon emission. Also, the area, $A_{l,t}^{PL}$is constrained by the availability of land, $A_{l,t}^{Max}$.

## 3. Mathematical formulation

### 3.1 Material balance

The material balance is formulated based on the superstructure presented in Figure 1. A typical sago palm weighs about 500 kg which are cut down to 10 – 12 logs. This is accounted into the model using conversion factors, $Y_l^{Palm}$ and $Y_l^{Log}$. $Y_l^{Palm}$ (logs/palm) is the number of logs cut from a palm while $Y_l^{Log}$ (t/log) is the average weight of a log. The total yield of sago logs at land type $l \in L$, $F_{l,t}^{Palm}$ (t/y) can be determined as shown in Eq(1).

$$F_{l,t}^{Log} = N_{l,t}^{Palm} \times A_{l,t}^{PL} \times Y_l^{Palm} \times Y_l^{Log} \qquad \forall l \forall t \qquad (1)$$

where, $A_{l,t}^{PL}$ (ha) is the area of land type $l \in L$ to be determined for sago plantation expansion. This area should be less than the available area, $A_{l,t}^{Max}$ (ha) as shown in Eq(2).

$$A_{l,t}^{PL} \leq A_{l,t}^{Max} \qquad \forall l \forall t \qquad (2)$$

The harvested sago logs are processed at the sago mills to produce the products $p \in P$ as shown in Eq(3)

$$F_{p,t}^{Product} = \sum_{l=1}^{L} F_{l,t}^{\mathrm{Log}} \times Y_p^{Cnv\_R} \qquad \forall p \forall t \qquad (3)$$

where, the conversion ratio of logs to product $p \in P$at the mill is denoted by parameter, $Y_p^{Cnv\_R}$. The total production of the product *p* during the period *t*, $F_{p,t}^{Product}$ (t) should satisfy the market demand at the period *t*, $D_{p,t}^{Product}$ (t) as shown in Eq(4).

$$F_{p,t}^{Product} \geq D_{p,t}^{Product} \qquad \forall p \forall t \qquad (4)$$

A detailed explanation on the material balance equations is presented by Rajakal et al. (2020).

### 3.2 Expansion cost

When the product (sago starch) demand is not met by the existing plantations, then there is a need for plantation expansion. An expansion will result in the LUC of the land type $l \in L$ to sago plantation. LUC involves cost depending on the current land use. This cost is referred as expansion cost, $Cost_l^{Exp}$ (USD/ha) that includes land clearing cost and sago planting cost. The total expansion cost for the period *t,* $Cost_t^{Expansion}$ (USD) is determined as shown in Eq(5).

$$Cost_t^{Expansion} = \sum_{l=1}^{L} A_{l,t}^{PL} \times Cost_{l,t}^{Exp} \qquad \forall t \qquad (5)$$

### 3.3 Carbon emission

LUC results in carbon emission or sequestration based on the change in carbon stock. When the difference in carbon stock is positive it results in sequestration; otherwise, it leads to emission. In this case, potential LUC are the conversion of highly carbon stocked ecosystems like forests, swampy lands, etc. to sago plantations. Like expansion cost, carbon emission from LUC depends on the current land use and is denoted as $Carbon_l^{Exp}$ (t $CO_2$-eq/ha/y). The total emissions due to LUC for sago plantation expansion during the period *t,* $Carbon_t^{Expansion}$ (t $CO_2$-eq) is determined as shown in Eq(6).

$$Carbon_t^{Expansion} = \sum_{l=1}^{L} A_{l,t}^{Exp} \times Carbon_{l,t}^{Exp} \qquad \forall t \qquad (6)$$

### 3.4 LUC optimisation

The area of land type $l \in L,$ $A_{l,t}^{PL}$ (ha) determined for plantation expansion is based on the objective variables – expansion cost or carbon emission. As discussed in Section 1, these objectives are conflicting in nature. The expansion cost is proportional to the density of the vegetation in the land while carbon emissions are due to biomass degradation and soil decomposition. A land with scarce vegetative cover but with highly stocked soil carbon will have less expansion cost but high carbon emissions. To address these conflicting objectives and to identify the most suitable strategy for expansion, a pareto multi-objective optimisation is used. In this work, pareto set is generated using $\varepsilon$-constraint method. The $\varepsilon$-constraint method translates multi-objective problem to single objective problem by considering any one of the two objective functions – minimise expansion cost or minimise carbon emission. The maximum ($f_j^{\max}$) and minimum ($f_j^{\min}$) value of that objective function is determined. Pareto set ($\varepsilon_j$) is then generated by constraining that objective function between the maximum and minimum values by imposing evenly distributed scalar weights. The corresponding values of the other objective variable is also noted to complete the Pareto set. A more detailed explanation of $\varepsilon$ constraint method is presented by Emmerich and Deutz (2018). Eq(7) – (9) presents the formulations to generate a pareto set. The pareto set is then plotted against expansion cost and carbon emissions to obtain the pareto frontier, which represent the range of optimised solutions for the multi-objective problem.

$$Minimise\ F(X) = f_i(x) \qquad x \geq 0 \qquad (7)$$

$$f_j(x) \leq \varepsilon_j \qquad j \neq i; j = 1 \dots n; x \geq 0 \qquad (8)$$

$$f_j^{\min} \leq \varepsilon_j \leq f_j^{\max} \qquad j = 1 \dots n \qquad (9)$$

## 4. Case study

The developed mathematical formulation is demonstrated using an illustrative case study in this section. The superstructure of the considered sago value chain is presented in Figure 2. The lands of different current land use that are considered for sago plantation expansion are presented in Table 1. The presented land reflects the type of lands available in southeast Asian countries that are suitable for sago palm growth. The maximum land area available under each current land use type, $A_{l,t}^{Max}$; the expansion cost, $Cost_l^{Exp}$ and carbon emissions, $Carbon_{l,t}^{Exp}$ are also presented in Table 1. Annual harvest ($N_{l,t}^{Palms}$) of 100 palms/ha/y is considered with the conversion factors,$Y_l^{Palm}$and $Y_l^{Log}$ taken as 10 and 0.05. At the mill, the conversion factor, ($Y_p^{Cnv\_R}$) of sago log to sago starch, sago bark and sago fibre is considered as 0.20, 0.28 and 0.35 (Wan et al., 2016). The sago starch demand is expected to increase to 10,000 t for the period *t*.

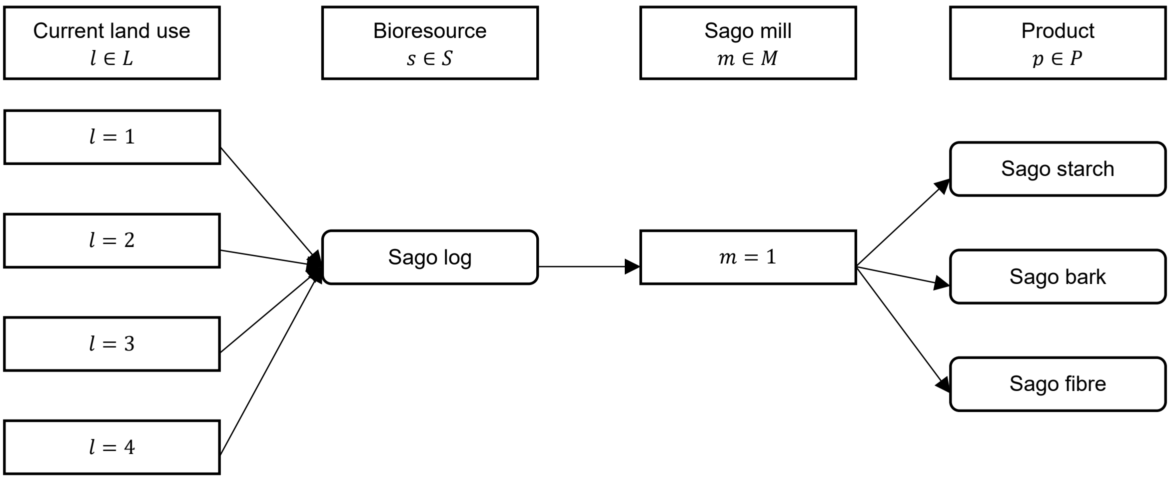


*Figure 2: Superstructure of the considered case study*

The sago log production from the existing plantations is 25,250 t producing 5,050 t of sago starch. The expected demand for sago starch is 10,000 t which translates to production deficit of 24,750 t of sago log. In order to meet the deficit, the developed model is used to determine the optimal area of lands for sago plantation expansion. The model is of the class linear programming (LP) and is solved using the LINGO version 18 in an Intel® Core (TM) i5 processor built in a 64-bit Windows operating system. The computational time taken to determine the optimal Pareto points in the set were less than 2 s.

*Table 1: Lands considered for sago plantation expansion*

| Land | Current land use | Max area available (ha) | Expansion cost (USD/ha) (Samad et al., 2009) | Carbon emission (t $CO_2$-eq/ha) (Agus et al., 2013) |
|---|---|---|---|---|
| L1 | Sago plantation | 505 | 0 | 0 |
| L2 | Degraded tropical forest | 850 | 2,510 | 8.60 |
| L3 | Degraded peatland | 430 | 2,385 | 29 |
| L4 | Swampy shrubland | 80 | 1,850 | 24.30 |

## 5. Results and discussion

The optimal value of carbon emission obtained during the single objective function - minimise carbon emission is 4,257 t $CO_2$-eq/y. Evenly distributed incremental scalar weights are used to generate Pareto frontier as shown in Figure 3a. The Pareto frontier provides the flexibility to the decision maker to choose an optimised trade-off solution. For example, in certain cases carbon emission cap for LUC are set by policy maker. In such cases, an optimised trade-off is chosen accordingly. Figure 3b plots the annual emission density to the annualised expansion cost. This will help the decision maker to foresee the investments to be made on plantation expansion for the different emission caps that the policy maker (government) can enforce. The corresponding LUC strategies are presented in Figure 4.

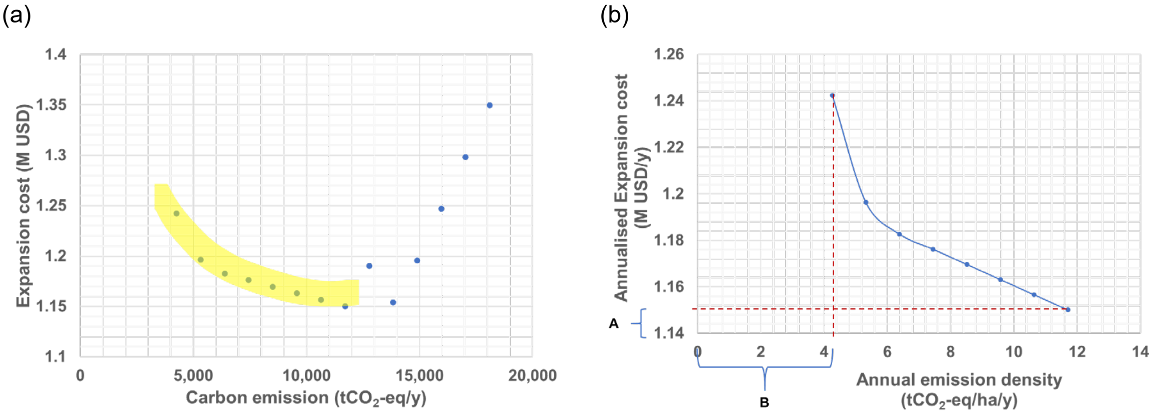


*Figure 3: Results of (a) Pareto frontier derived from ε -constraint method and (b) annual emission density vs annualised expansion cost*

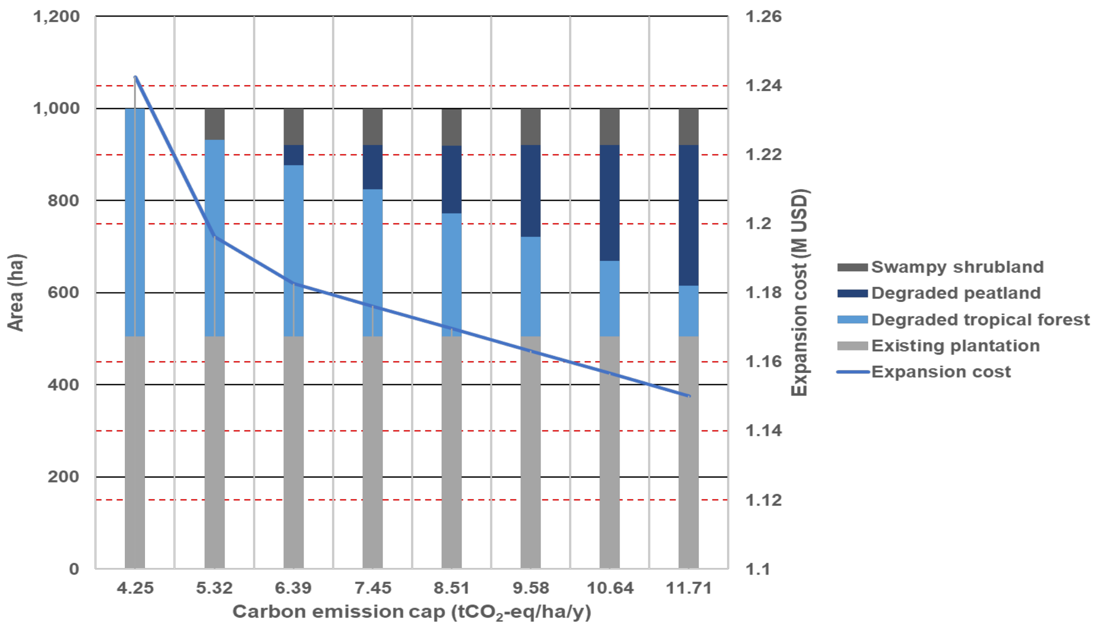


*Figure 4: Expansion strategies for considered sago starch demand*

Figure 4 shows that the minimum (annualised) expansion cost to meet the expected demand is 1.15 M USD (A) while the minimal emission density that is absolutely inevitable to meet the demand is 4.25 t $CO_2$-eq/ha/y (B). Further the different expansion strategies with their corresponding expansion cost is presented in Figure 6. The existing plantations are utilised to its fullest. It can be observed that as the emission cap increases, the area under degraded forest decreases while that of degraded peat land increases. This is because the expansion cost of degraded peatland is 5 % lesser compared to degraded tropical forest.

## 6. Conclusion

This work presents a multi-objective linear programming model for sustainable sago plantation expansion, accounting for expansion cost and carbon emission. The multi-objective problem is solved by generating Pareto frontier by epsilon constraint method. The developed model is simple in mathematical rigour but provide significant and insightful results for planning and decision making. It finds more suitable application at macro level like a country or a region. The main contribution of this work includes synthesise of sustainable LUC strategies for sago plantation expansion. The results can aid in planning the land pooling activities for new plantation expansions with minimal environmental footprint. Also, the results can help realise the investments that will be required under different climate change policies. The contributions of this work assume significance as it comes as a response to the global call for sustainable land resource management in agricultural expansion.

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