Received: 27 December 2022 | Revised: 4 March 2023 | Accepted: 10 March 2023

DOI: 10.1002/glr2.12044

RESEARCH ARTICLE

Grassland Research Open Access

Feed profile analysis of oil palm-integrated beef cattle farming systems by metabolic energy budgeting and implications for beef production and pastoral system design

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Handling Editor: Zhibiao Nan

Funding information

The Government of Malaysia through Universiti Malaysia Sabah and the Ministry of Higher Education of Malaysia, Grant/Award Numbers: GKP0019-STWN-2016, SDK0010-2017

Abstract

Background: Oil palm is a tropical crop with worldwide plantings approaching 20 million ha and large areas in Indonesia, Malaysia and Thailand. The plantations are readily managed as silvopastoral systems incorporating cattle grazing (Oil Palm Silvopastoral System for Cattle, OPSC) but there is a need for analytical tools and data to understand system herbage supply and feed conversion efficiency (FCE).

Methods: Metabolic energy budgeting was used to estimate herbage harvested by cattle in three OPSC subsystems, 9 and 12 years after oil palm establishment, and FCE of the subsystems was determined. Understorey herbage was also analysed for nutritive value, botanical composition and herbage accumulation within one grazing-regrowth cycle.

Results: The herbage-harvested estimate was 2.0−2.4 t dry matter (DM) ha^{-1} $year^{-1}$ for 9 year old subsystems and 1.4−1.7 t DM ha^{-1} $year^{-1}$ for a 12 year old subsystem. Herbage metabolisable energy (ME) was 8.3−8.5 MJ kg^{-1} DM and crude protein (CP) was 15%−16% DM. FCE values for subsystems ranged from 32 to 94 kg DM kg^{-1} liveweight-gain.

Conclusions: Herbage DM yield is declining, while herbage ME is marginal but CP is adequate. FCE is suboptimal but can be optimised by defining the trajectory of declining herbage production with canopy closure as plantations age and matching stocking rate to herbage supply using a comparative-stocking-rate-type statistic.

KEYWORDS

beef cattle production, farm feed profile, feed conversion efficiency (FCE), metabolic energy budgeting (MEB), Oil Palm Silvopastoral Systems (OPS)

INTRODUCTION

Oil palm is an important crop in many tropical countries worldwide, including Indonesia, Malaysia, Thailand, Colombia, Nigeria and others, where it is grown to produce oil, meal and other derivatives, resulting in significant economic growth from the international trade (Murphy et al., 2021). Despite concerns about forest conversion to oil palm plantations and the deterioration of ecosystem well-being (Khasanah et al., 2020), it is well accepted that oil palm and oil palm plantations are economically important for gross domestic product growth and poverty alleviation in the countries where oil palm is grown (Naylor et al., 2019). The global area of oil palm plantations is 19.0−19.6 million ha (Descals et al., 2021; Murphy et al., 2021), of which 8.0 million ha are located in Indonesia and 5.74−5.87 million ha are in Malaysia (Murphy et al., 2021; Parveez et al., 2021, 2022). Besides oil palm fruit production, these areas are also used silvopastorally for livestock rearing (Oil Palm Silvopastoral System, OPS), especially for beef cattle production (OPS for cattle, OPSC). Initially, cattle were introduced into oil palm plantations to control understorey weeds but were later farmed systematically to produce beef commercially (Azizol & Norlizan, 2004; Chen, 1990; Kabul, 2008). Many plantation managers, however, are reluctant to implement oil palm systems with integrated cattle browsing because of increased staff workload, cost of hiring new staff and purchasing new devices for cattle husbandry, the potential for soil compaction or damage to drainage systems, concern over livestock theft and security issue, and concern to focus on the core plantation business (Bremer, de Bruyn, Smith, & Cowley, 2022; Wong, 1998; Zamri-Saad & Azhar, 2015). Also, both in tropical pasture grazing systems and OPSC systems, there is a general lack of data and analytical tools to guide managers on basic questions like the stocking rate of cattle in plantations of various ages to provide appropriate feed allocation for cattle. As a result, the stocking rate is often too high or too low to optimise feed conversion efficiency (FCE). In most cases, the cattle are underfed and not growing to their genetic potential, and managers are under pressure to justify to stakeholders, the merits of retaining cattle in the plantations. The use of large land areas solely for oil palm cultivation has contributed to an overreliance on imported beef to meet local demand. In Malaysia, for example, beef importation incurred a foreign exchange cost of 2.2 billion Malaysian ringgit (Ringgit Malaysia, RM) per year (DOSM, 2021).

In a successful oil palm-cattle integration, the benefits can be substantial (Azhar et al., 2021; Grinnell et al., 2022). Integration of livestock in a plantation was reported in one case to increase fresh fruit bunch yield from 15−20 to 26−30 t ha^{-1} $year^{-1}$ (Wahab et al., 2021). In other cases (Lam et al., 2009; Tohiran et al., 2019), undergrowth in the plantation and infestation of the oil palm crop canopy by a climbing weed following establishment failure of a cover crop had resulted in significant herbicide usage and concerns about herbicide pollution to the wider environment, but the introduction of cattle to the plantation resulted in decreased herbicide use and increased revenue. The introduced cattle provided biological control for the weeds: 373−1027 cattle were grazed on 974−2394 ha, split into smaller blocks on the plantation, confined by electric fences; the cattle were moved to a new block daily (Ayob & Kabul, 2009). As a result, weeds were grazed to the ground level, and after several years, the cattle were sold at RM 5.50−6.50 kg^{-1} liveweight (LWT) (Latif & Mamat, 2002) to RM14.50 kg^{-1} LWT as quoted by a plantation company in Sabah in 2021. Issues such as soil compaction and destruction to drainage systems arising from the introduction of cattle were reported to be superficial, but this did depend on the stock number (Wong, 1998).

In Malaysia and Indonesia, although some of the understorey vegetation species are unpalatable and often avoided by livestock (e.g., *Melastoma* spp. and *Mikania* spp.), there are many shade-tolerant grasses (*Paspalum conjugatum*, *Axonopus compressus*, and *Brachiaria miliformis*), legumes (*Desmodium* spp., *Calopogonium* spp., and *Mucuna* spp.), and broadleaved weeds (*Asystasia* spp.) available for cattle to graze (Dahlan et al., 1993; Grinnell et al., 2022). In OPSC, however, a fundamental issue for planning and management of the stocking rate is the lowering of herbage dry matter yield and metabolisable energy (ME) and crude protein (CP) levels, which occur in response to a progressive decrease in light intensity reaching understorey vegetation (Supporting Information: Figure S1) as the oil palm trees in the plantation develop from isolated single plants to canopy closure and as understorey herbage matures during its regrowth cycle. For instance, in one study on understorey plants and oil palm age (Dahlan et al., 1993), the light penetration was reported to be 100% when the palms were 2 years old, 40% when 10 years old and 20% when 15 years old; the understorey dry matter production at each of the three canopy closure stages was 4, 2 and 1 t DM ha^{-1} $year^{-1}$, respectively. Another researcher reported that in a 3−4 year old unweeded oil palm plantation, herbage dry matter yield was approximately 3.0 t DM ha^{-1} $year^{-1}$ (though in some cases up to 9.5 t DM ha^{-1} $year^{-1}$), decreasing to 400−800 kg DM ha^{-1} $year^{-1}$ by the time the plantation was 6−7 years old (Chen, 1990). The understorey herbage production was reported to remain at 400−800 kg DM ha^{-1} $year^{-1}$ for the next 20 years (Jalaludin & Halim, 1998). The energy production of herbage available for grazing was reported by Dahlan et al. (1993) to decrease from 34 MJ ME ha^{-1} day^{-1} in a 3 year old oil palm plantation to 10 MJ ME ha^{-1} day^{-1} in a 15 year old oil palm plantation. There was a corresponding decrease in CP from 12.7% to 9.2% of the understorey plant DM in 9−16 year old plantations when grasses replaced the broad leaf plants in older plantations (Wattanachant et al., 1997).

This declining energy availability for grazing animals and fall in CP to near the reported minimum for the ruminant diet of 6%−8% (Humphreys, 1991) with plantation age would likely limit the cattle carrying capacity of older plantations. However, the deductions that can be drawn from them are rather qualitative. There is a need for objective information for plantation managers to allow them to adjust the stocking rate in parallel with dry matter production and herbage nutritive quality decline of the understorey vegetation so that the health of adult cattle kept for breeding purposes and the growth of young cattle intended for sale are not jeopardised. One methodology not so far employed in this context to our knowledge, to define the capacity of an oil palm plantation to support livestock, is metabolic energy budgeting (MEB) for cattle in an actual grazing situation. This methodology is widely used in farm system optimisation, farm system research, and government planning in a number of countries (Gobilik et al., 2021).

The present study was carried out in 2014 in Sabah, where there was about 1.53 million ha of agricultural land planted with oil palms (Parveez et al., 2022). The plantations were stated by Kabul (2008) to be increasingly used for beef cattle farming for profit maximisation and the trend has continued. One plantation operator reported in 2010 that it carried 8018 cattle on 22 949 ha of oil palm plantations, and in 2022, there were 15 000 head of cattle (SKSB, 2010, 2022). The oil palm company that agreed to participate in this study has been involved in OPSC farming since the 1990s and has a well-organised rotational stocking system in its oil palm plantations (Kabul, 2008; SKSB, 2022). The focus of this analysis was to use MEB (Gobilik et al., 2021) to quantify the energy requirements of cattle in monthly time steps in three separate OPSC subsystems in Sabah: two 9 year old plantations (9OP1 and 9OP2) and one 12 year old plantation (12OP). With supporting secondary information from limited-duration herbage accumulation measurements and nutritive value analyses, calculated values of energy required by cattle from MEB were converted to estimates of herbage dry matter harvested. These estimates were compared with theoretical potential herbage accumulation based on light availability, based on the methods described by Wilson and Ludlow (1990) and Cooper (1970), and the potential application of these data for optimisation of the stocking rate in OPSC plantations was explored.

MATERIALS AND METHODS

Case OPSC systems: 9OP1, 9OP2 and 12OP subsystems

The 9OP1, 9OP2 and 12OP noted above were located in Lahad Datu in south-eastern Sabah (4°57′54″ N, 118°31′53″ E; 5–20 m a.s.l.). Based on the nearest weather station, the annual rainfall in these subsystems is 2286 ± 511 mm. The monthly average rainfall is highest in January (288 mm), then reduces to 118 mm in June and a low of 103 mm in August, before increasing again to 202 mm in December (DOA, 2015). The monthly mean temperature is highest from June to August (31°C) and lowest from December to January (26°C), although generally the temperature can be regarded as almost constant with an average of 28°C throughout the year.

Farm system details of 9OP1, 9OP2 and 12OP OPSC subsystems

9OP1 and 9OP2 OPSC subsystems were adjacent to each other and had been farmed for the previous 5–6 years as a single unit. Operation of 9OP1 and 9OP2 as independent single units for cattle farming commenced in November 2013. 12OP was situated 3–4 km from 9OP1 and 9OP2. It has been used for cattle farming for about 5–7 years. The total area of subsystem 9OP1 was 760 ha, while subsystems 9OP2 and 12OP were both 360 ha. Average paddock sizes were 13 and 6 ha, respectively, for subsystems on 9OP1 and 9OP2, while the paddock size of 12OP was also 6 ha. 'Paddock' is used here for simplicity to refer to the grazing area enclosed temporarily by the company staff, using electric fencing.

The topography of 9OP1 and 9OP2 can be described as flat to gently undulating. Soil data collected from the subsystems in August 2014 were pH, 5.0 ± 0.1; total N, 0.1% ± 0.0; available P, 51.5 ± 9.4 ppm; K, 0.5 ± 0.3 meq %; Ca, 4.0 ± 1.9 meq% and Mg, 1.8 ± 1.5 meq%. The topography of 12OP was similar to that of 9OP1 and 9OP2. Soil samples were not collected, but similar values to 9OP1 and 9OP2 would be expected.

The cattle on all subsystems were Brahman and all bull sires and breeding cows were cattle of certified breed imported from Australia. The management of cattle on the subsystems had varied historically, depending on the policies of particular past managers. At the time of data collection, 9OP1 was used for breeding cows (with calves at foot) and bulls; 9OP2, for weaner female cattle and some weaner male cattle (6–24 months old); and 12OP, for weaner male cattle (6–24 months old). The heifers joined the cows in 9OP1 at approximately 24 months of age for breeding. The stocking rate was less than one animal per hectare on all three subsystems (Table 1).

The grazing interval on all subsystems was 60 days. The cattle were transferred to a new paddock every day, confined with temporary electric fencing. The cows and bulls were run together throughout the year, and cows calved almost every month, though with a greater frequency in the March–May period. As mentioned above, weaned female calves were transferred to other oil palm plantations in Sabah belonging to the company, and weaned female calves from the other plantations were transferred to 9OP2 to avoid inbreeding. Weaned male calves were transferred to 12OP or 9OP2, and at 24 months old, the bulls were transferred to a cut-and-carry feedlot cattle system for finishing.

Based on farm records, the calving rate was approximately 33%–40% per year. The average calf birth weight was reported to be 18–18.5 kg. The male and female calves were weaned between the ages of 6 and 12 months (average of 10 months). The average weaning weight was 130 kg and the average weight at 24 months was approximately 233 kg; the average daily gain was 368 g head^{-1} day^{-1} from birth to weaning and 242 g head^{-1} day^{-1} from weaning to 24 months.

TABLE 1 Average stocking rate and liveweights of cattle on 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems with integrated cattle browsing.

Item	Cattle classes	9OP1 2013	9OP1 2014	9OP2 2014	12OP 2013	12OP 2014
Effective area (ha)		495	495	234	303	303
Number of cattle (head)	Cows	304	243	64	0	0
	Bulls	13	11	2	0	0
	Calves	138	89	21	4	1
	Heifers	0	0	–	162	38
	Weaner bulls	0	0	87	0	152
Stock (head ha^{-1})		0.92	0.69	0.74	0.55	0.63
Liveweight (kg head^{-1})	Cows	378	386	377	–	–
	Bulls	451	474	474	–	–
	Calves	57	106	72	78	49
	Heifers	–	–	–	215	281
	Weaner bulls	–	–	187	–	187

Data collection

Acquisition of cattle data

The cattle records used for MEB (see Modelling of monthly and annual feed demand and consumption section, below) were supplied by the farm operation manager and covered the periods from January 2013 to December 2014 for 12OP and 9OP1 and from January 2014 to December 2014 for 9OP2. The records available included details of the number of cattle in various classes recorded monthly (overall, 600−700 head), but body weight data supplied to the author was averaged across stock classes, with data for individual cattle classes only available for important events; primarily birth, weaning, 24 months old and selling. To obtain monthly body weight estimates for individual cattle classes for modelling purposes, relevant live weight trajectories of cattle on a government cattle breeding farm in the district nearest to these subsystems were obtained and used to interpolate cattle weight trajectories between the measured values supplied as presented in Appendix 6.1 of Gobilik (2017). In this data set, the mean growth rate for female animals was 391 g head^{-1} day^{-1} from birth to 10 months old and 249 g head^{-1} day^{-1} from 10 to 24 months old. Corresponding values for male animals were 344 and 283 g head^{-1} day^{-1}, respectively.

Measurements of effective area

The 'effective area' for MEB was calculated (as distinct from the total farm area) by first selecting 3 ha as representative of the total area on each subsystem and mapping in detail the areas not available for grazing and deducting these from the total area. The areas excluded from the effective area included tree trunks and associated circle weeding, stacked pruned palm fronds, and drains and roadways (Table 2).

TABLE 2 Effective area of 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems with integrated cattle browsing.

Area	OPSC subsystem		
	9OP1	9OP2	12OP
Total area (ha)	760	360	360
Nongrazeable area (ha)	265	126	57
Area under stem per hectare	0.016	0.016	0.016
Area under circle weeding per hectare	0.173	0.173	0.043
Area under frond debris per hectare	0.12	0.12	0.06
Area of road per hectare	0.02	0.02	0.02
Area of drain per hectare	0.02	0.02	0.02
Effective area (ha)	495	234	303

Note: Nongrazeable area is obtained by summing the areas per hectare occupied by stems, circle weeding, frond debris, roads and drains and multiplying by the total area and was assumed to be the same in 2013 as in 2014. The densities of oil palm trees in each OPSC subsystem were 138 trees ha^{-1}.

Abbreviations: OPSC, oil palm silvopastoral system for cattle.

Available data on feed supply

As in the studies by Gobilik (2017) on cut-and-carry feedlot and open-pasture grazing cattle systems in Sabah, the primary thrust of this study was to define the system through the cattle demand calculated by MEB. However, available information on feed supply and the nutritive value of the feed was also collected to support the discussion of the modelling results.

(a) Herbage accumulation assessment:

Data on herbage dry matter yield and botanical composition on each subsystem were collected three times during August–September 2014. A first series of herbage cuts was carried out to assess herbage mass in five selected paddocks: 60, 45, 30, 15 and 1 day before grazing commenced. The sample collection was carried out on the same day on all subsystems. The second and third series of sampling cuts were carried out on the same paddocks 15 days after grazing and again 30 days later. Ten 0.26 m^2 quadrats were placed at 10 m intervals towards the centre of each paddock. The starting location for sampling was approximately 10 m inside the paddock, selected by a throw of a stick to preclude human bias in selecting the starting point. A sample of cut herbage from outside of each quadrat was preserved for assessment of botanical species composition. Botanical identification was achieved by comparison with specimens deposited in the Sandakan Herbarium, Sabah. A subsample from each quadrat was separated into leaf, leaf sheath, stem and dead matter. Each of the main samples and the components of the sorted subsample were weighed, dried at 60°C for 2 days and reweighed. Additional details are given by Gobilik (2017).

(b) Herbage ME and CP analysis:

Dried herbage from Quadrats 2, 5 and 8 from each transect of the sampling described earlier were ground to powder and sent to Makmal Kesihatan Awam Veterinar, Department of Veterinary Services, West Malaysia (Lab references ST3385/14 and ST3596/14) for the analyses of ME, CP and crude fat contents following protocols set out in the Malaysian Standard of Test for Animal Feedstuffs MS: 3.1982.

Analysis of system feed profiles

Modelling of monthly and annual feed demand and consumption

The metabolic energy requirements of the cattle were assumed to be the feed demand of the system and were taken to represent the feed harvested by cattle in the system, as in Gobilik (2017). Metabolic energy calculations to determine feed demand were performed for all three subsystems, for each month. The Microsoft® Excel spreadsheet model developed for the analysis performs a separate calculation of energy requirements for individual cattle classes based on the relevant liveweight trajectories of the classes and the results were multiplied by the number of cattle in each class to arrive at a total for each subsystem. Based on laboratory results for herbage ME and the 'effective area' (Table 2) of the respective subsystems, the herbage DM data were presented as kg DM ha^{-1} day^{-1} or t DM ha^{-1} $year^{-1}$ according to the context of the discussion. As feed supplement was not used, no adjustment for supplement used was made when estimating herbage demand from the cattle metabolic energy demand. The detail of the metabolic energy equations used has been previously described elsewhere (Gobilik, 2017; Gobilik et al., 2017, 2021). Specifically, the metabolic energy requirements of each animal were calculated for body maintenance, liveweight gain, chewing and rumination associated with herbage intake, pregnancy, lactation and walking activity (Gobilik, 2017). The basic equation for the calculation of daily metabolic energy requirements of grazing cattle is:

$$ME_d = k_1 LWT^{0.75} + k_2 LWGL + ME_{ChR} + ME_{Pr} + ME_{La} + ME_{WA},$$

where ME_d is the daily ME requirement per head; LWT is the animal liveweight (as defined above); k_1 is a function of animal species, sex and age; LWGL is the liveweight gain or loss; k_2 differs for gain and loss and in the case of loss differs for lactating and nonlactating animals; ME_{ChR} is the energy cost of chewing and ruminating herbage consumed and is dependent on animal species, herbage intake and herbage digestibility; ME_{Pr} is the energy required by pregnant animals to support conceptus growth or is zero for nonpregnant animals; ME_{La} is the energy required to support metabolic demands of lactation or is zero for any animal not lactating and ME_{WA} is an allowance for walking and related activity and is primarily a function of distance walked per day and animal body weight (Gobilik, 2017; Nicol & Brookes, 2007).

FCE

Information on feed demand and cattle liveweight gain was extracted from the above analyses and FCE was calculated as the total feed demand (per month or per annum) divided by the total liveweight gain in the same period for periods of interest. It should be noted that for the interpretation of the data lower values represent higher FCE and that breeding systems producing calves will have intrinsically lower FCE values than systems designed to increase the body weight of weaned calves.

Theoretical potential herbage production

For benchmarking the estimate of herbage supply of the herbage cutting and MEB, theoretical potential herbage production based on light availability estimate under oil palms was calculated using the method adapted from Wilson and Ludlow (1990) and Cooper (1970) as set out in Appendix 6.2 of Gobilik (2017). The calculation was based on daily solar energy input in Sabah (15.87 MJ m^{-2} day^{-1}; Kartini et al., 2015), assuming light penetration through the oil palm canopy of 46% for a 9 year old plantation and 30% for a 12 year old plantation (Dahlan et al., 1993); light captured by herbage to be 51.5% (Wilson & Ludlow, 1990); light energy as photosynthetically active radiation (PAR) or photon irradiance on the herbage canopy to be 27% (Baldocchi et al., 1984) and conversion of PAR light energy to herbage dry matter of 3.5% (Cooper, 1970).

RESULTS

System feed profiles based on MEB

The MEB indicated that the annual feed demand of the system ranged from 2.0 to 2.4 t DM ha^{-1} $year^{-1}$ for 9OP1/9OP2 and from 1.4 to 1.7 t DM ha^{-1} $year^{-1}$ for 12OP (Table 3). Feed supplement was not used on all subsystems, so, vegetation under the oil palms, and sometimes ferns on the palm trunks and oil palm fronds, was the main source of feed for the cattle. The monthly feed demand per cattle ranged from 250 to 256 kg DM $head^{-1}$ for 9OP1/9OP2 and 198 to 204 kg DM $head^{-1}$ for 12OP. Counterintuitively, no spike in monthly feed demand was detected on 9OP1 (cow–calf subsystem) during March–May and August–October concentrated calving or weaning (September–October and February–March) periods (Figure 1). Monthly feed demand showed some marked fluctuations towards the end of the year on all subsystems, but these were attributable to the movement of cattle between the subsystems or oil palm plantations belonging to the company.

FCE

The average FCE of the subsystems was 32.2 ± 3.0, 45.9 ± 13.8 and 94.0 ± 24.7 kg DM kg^{-1} LWG for 12OP, 9OP2 and 9OP1, respectively (Figure 2). Overall, it was 57.4 ± 9.8 kg DM kg^{-1} LWG. FCEs were low when there

TABLE 3 Feed demand of cattle in 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems with integrated cattle browsing.

OPSC subsystem	Year	Feed demand (t DM ha^{-1} $year^{-1}$)	Feed demand (kg DM $head^{-1}$ day^{-1})	Energy demand (GJ ha^{-1} $year^{-1}$)
9OP1	2013	2.40	8.44	20.42
	2014	2.00	8.23	17.03
9OP2	2014	2.02	7.53	17.15
12OP	2013	1.42	6.52	12.06
	2014	1.68	6.71	14.28

Abbreviations: DM, dry matter; OPSC, oil palm silvopastoral system for cattle.

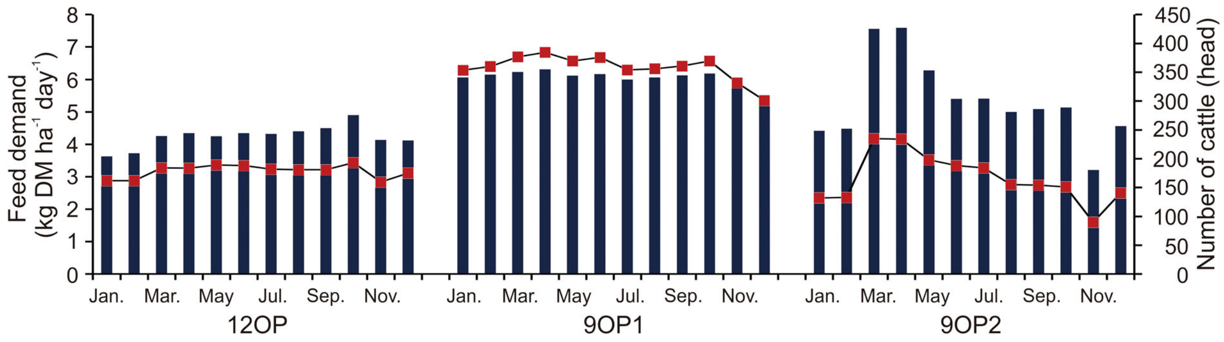

FIGURE 1 Monthly feed demand (bars) and number of cattle in 12 year old (12OP) and 9 year old (9OP1, 9OP2) oil palm systems with integrated cattle browsing. DM, dry matter.

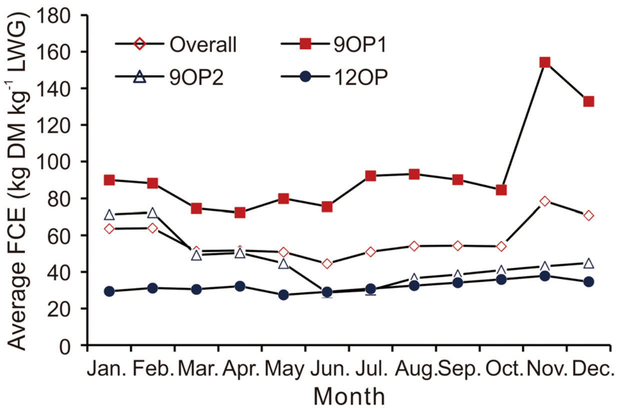

FIGURE 2 Average monthly feed conversion efficiency of 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems with integrated cattle browsing. DM, dry matter; FCE, feed conversion efficiency; LWG, liveweight gain.

were new calves with 1 year old calves not yet weaned (Figure 2: November–December 9OP1). The months of most efficient FCE for each system were April, June and May for 9OP1, 9OP2 and 12OP with 72.3, 28.8 and 27.5 kg DM kg^{-1} LWG, respectively. The coefficient of variation across months for monthly FCE ranged from 9% (12OP) to 30% (9OP2).

Information on feed supply from short-term observations

Herbage accumulation from 2 month cutting experiments

In the cutting experiment, the average green dry matter increment during the 60 day grazing interval was 17.8 kg DM ha^{-1} day^{-1} for 9OP1/9OP2 and 10.1 kg DM ha^{-1} day^{-1} for 12OP (Table 4). If it can be assumed that these data are also representative of herbage accumulation in months not sampled (see Discussion, Seasonality of herbage demand and production section, below), then annualised green dry matter accumulation was 6.5 t DM ha^{-1} year^{-1} for 9OP1/9OP2 and 3.4 t DM ha^{-1} year^{-1} for 12OP. The average green dry matter production of 12OP was 48% less than that of 9OP1/9OP2. The average leaf dry matter accumulation during the 60 day grazing interval was 10.1 kg DM ha^{-1} day^{-1} for 9OP1/9OP2 and 6.3 kg DM ha^{-1} day^{-1} for 12OP (Table 4). Annualised leaf dry matter was 3.7 t DM ha^{-1} year^{-1} for 9OP1/9OP2 and 2.3 t DM ha^{-1} year^{-1} for 12OP.

Herbage botanical composition

The botanically important species on all OPSC subsystems were similar (Supporting Information: Table S1). In total across all quadrats, 14 species were found, of which two were identified only to the genus level, and two other taxa (one fern and one unknown) could not be identified. There were 9 species on 9OP1/9OP2 and 12 species on 12OP. Two species, *A. compressus* and a *Digitaria* sp., on 9OP1/9OP2 were not recorded on 12OP, and five species of mostly broadleaf plants on 12OP were not recorded on the other two subsystems (Supporting Information: Table S1). *Ottochloa nodosa*, *Asystasia gangetica*, *A. compressus*, *Panicum* sp. and *P. conjugatum* were the important species on 9OP1/9OP2. With the exception of *A. compressus*, the four other species and *Cyrtoccocum patens* were also numerous on 12OP.

Herbage ME and CP content

On all three OPSC subsystems, there was no obvious change in herbage ME through the regrowth cycle and values averaged 8.4 MJ kg^{-1} DM, with comparatively little variation. Herbage CP (%) varied little during the grazing cycle on 9OP1/9OP2 and tended to be lower on 12OP than on 9OP1/9OP2 (Table 5). At the time the cattle were transferred to a new paddock, herbage ME was 8.3 and 8.5 MJ kg^{-1} DM and CP was 16.3% and 15.4% DM on 9OP1/9OP2 and 12OP, respectively.

Theoretical potential herbage production

The theoretical potential herbage production was 6.97 t DM ha^{-1} year^{-1} in 9 year old oil palm plantations and 4.55 t DM ha^{-1} year^{-1} in 12 year old oil palm plantations. When only the areas available for grazing and leaf production were considered, the theoretical potential production was 4.53 t DM ha^{-1} year^{-1} (total DM) and

TABLE 4 Herbage accumulation rate in 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems at various stages in the regrowth cycle of the 60-day rotation.

OPSC subsystem	Stage of regrowth (days)	Herbage accumulation rate (kg DM ha^{-1} day^{-1})					
		Growth	Green matter	Leaf	Leaf sheath	Stem	Dead matter
9OP1/9OP2	60–45	24.4	22.7	15.4	3.9	3.4	1.7
	45–30	−3.1	−4.1	−4.1	0.5	−0.6	1.0
	30–15	22.2	22.1	11.9	5.0	5.2	3.8
	15–0	36.0	26.3	13.1	3.8	9.4	6.1
12OP	60–45	−20.5	–13.8	–5.1	–3.0	–5.7	–6.7
	45–30	18.6	13.5	6.1	4.6	2.8	5.1
	30–15	9.4	9.7	6.8	1.6	1.4	–0.4
	15–0	13.1	14.0	12.3	3.1	4.8	–0.9

Note: Data were collected only during the months of August and September so must be interpreted with care.
Abbreviations: DM, dry matter; OPSC, oil palm silvopastoral system for cattle.

TABLE 5 Production and nutritive value of ground herbages in 9 year old (9OP1, 9OP2) and 12 year old (12OP) oil palm systems with integrated cattle browsing every 15 days within the 60 day grazing interval.

OPSC subsystem	Days before grazing	Production (kg DM ha^{-1})	CP (% DM)	ME (MJ kg^{-1} DM)
9OP1/ 9OP2	60	142 ± 38		
	45	483 ± 111	17.6	8.4
	30	421 ± 55	18.1	8.4
	15	752 ± 107	17.6	8.6
	0	1146 ± 239	16.3	8.3
12OP	60	338 ± 35		
	45	131 ± 20	16.8	8.4
	30	333 ± 58	14.5	8.1
	15	480 ± 79	10.2	8.6
	0	689 ± 201	15.4	8.5

Note: Samples at 60 days were not analysed for CP and ME content.
Abbreviations: CP, crude protein; DM, dry matter; ME, metabolisable energy.

2.45 t DM ha^{-1} year^{-1} (leaf DM) in the 9 year old oil palm plantations and 2.95 t DM ha^{-1} year^{-1} (total DM) and 1.59 t DM ha^{-1} year^{-1} (leaf DM) in the 12 year old oil palm plantation.

DISCUSSION

Current status of the system and implications for beef production

Annual herbage demand and production

The reported herbage accumulation in 9–12 year old oil palm plantations in West Malaysia is generally 400–800 kg DM ha^{-1} year^{-1}. In one 3–4 year unweeded oil palm plantation, a production of 3 t DM ha^{-1} year^{-1} was reported, while in another case, 5.5–9.5 t DM ha^{-1} year^{-1} was reported but markedly lower values of 400–800 kg DM ha^{-1} year^{-1} were reported for a plantation that was 6–7 years old (Chen, 1990; Hassan, 2001). In another study, production was reported to remain at 400–800 kg DM ha^{-1} year^{-1} for the next 20 years from year 7 (Jalaludin & Halim, 1998). By contrast, (i) the estimated annual herbage accumulation of 6.5 t DM ha^{-1} year^{-1} for 9OP1/9OP2, based on the cutting experiment, and 3.4 t DM ha^{-1} year^{-1} for 12OP; (ii) the theoretical potential herbage production based on light availability (4.53 and 2.95 t DM ha^{-1} year^{-1} for 9OP1/9OP2 and 12OP, respectively) and (iii) the estimate of herbage harvested by cattle from MEB of 2.0–2.4 t DM ha^{-1} year^{-1} for 9OP1/9OP2 and 1.42–1.68 t DM ha^{-1} year^{-1} for 12OP indicated that herbage DM yields for beef production on the 9 and 12 year old oil palm plantations studied were all higher than these published values. Similarly, Grinnell et al. (2022) reported estimates of 858 and 443 kg herbage DM ha^{-1} year^{-1} harvested by cattle on two oil palm plantation blocks they studied in West Malaysia, also much lower than values from the present study. Also, data from Ivory Coast and Cameroon reported by Bremer, de Bruyn, Smith, Darsono et al. (2022) indicated a range of 73–122 cattle days grazing ha^{-1} year^{-1}, which would place herbage harvested at 0.44–0.73 t DM ha^{-1} year^{-1}, assuming 6.0 kg DM eaten head^{-1} day^{-1}. However, despite being greater than many published reports, the herbage supply estimated using MEB in this study is similar to the value of 1.5–2.0 t DM ha^{-1} year^{-1} recorded by Hassan et al. (2004) from a cutting experiment for a younger (5 year old) oil palm plantation.

Herbage harvested by cattle as determined by MEB were only half of the theoretical potential herbage production based on assumed light penetration. Herbage yields in the cutting experiment were higher than those from MEB or theoretical potential production. The difference between the results from the MEB calculations and the cutting experiment could arise from various factors including cattle only grazing the leaf, cattle refusing some patches of herbage or inconsistent grazing pressure. The leaf is preferred by cattle

(Chacon & Stobbs, 1976) probably because it is more nutritious than the stem and dead material (Lambert & Litherland, 2000) or possibly also because it tends to be mainly in the upper horizon of the sward and is therefore grazed first. In fact, when only leaf DM is considered, the difference between the results of the MEB and, for example, the cutting experiment is smaller (1.3–1.7 t DM ha^{-1} $year^{-1}$ for 12OP and 0.6–0.9 t DM ha^{-1} $year^{-1}$ for 9OP1/9OP2). From another perspective, MEB provides a reasonable estimate of operational herbage production in the system. Another factor contributing to the difference is herbage rejection; cattle are reported to reject forage near their faeces for more than a month (Dohi et al., 1991) and thus expected to graze less herbage during the next grazing event. This dung-avoidance behaviour was observed in this study as presented in Appendix 6.4 of Gobilik (2017) despite the grazing rotation being as long as 60 days. Another factor possibly influencing the relativity between cutting yield and other yield measures is the harvesting of herbage to the ground level when cutting, while grazing leaves residual herbage. This interpretation of the data is supported by a comment to the cattle farm manager (*pers. comm.*) from the plantation management group, advising that 9OP1 and 9OP2 were not satisfactorily clear of undergrowth.

Comparing the herbage production data of other authors (e.g., Chen, 1990; Jalaludin & Halim, 1998) with those reported in this study, it is clear that herbage production between plantations of similar age can differ. Hence, in terms of OPSC farm management, farmers need to adopt a stocking rate appropriate to their own site and not rely on data from other sites, however, generated. Herbage production differences between oil palm plantations can arise from a range of factors including differences in micro-ecological conditions, whether cattle or herbicides are used to control the undergrowth, the fertiliser regime and the extent of disease or insect predation of herbage. Reducing herbage production as oil palm plantations mature will always be primarily explained by the reduced amount of understorey light, linked to canopy closure with palm age(Dahlan et al., 1993; Germer, 2003). However, the interaction between solar radiation, oil palm age and soil nutrient level is complex; any factor altering oil palm frond expansion and thus the rate of reduction of understorey light will thus affect understorey herbage yield at a given palm age (Germer, 2003). These interactions are as yet little studied.

Seasonality of herbage demand and production

MEB results indicated that herbage demand in the studied subsystems is aseasonal, and the calculated intra-annual fluctuations in monthly herbage demand (Figure 1) were much smaller (minimum monthly average growth rate 40%–70% of maximum) than those observed in temperate pastures such as in New Zealand (minimum typically < 20% maximum, Gobilik et al., 2021). Moreover, within-year demand fluctuations (Figure 1) were largely attributable to the movement of cattle between different oil palm plantations belonging to the company. Stock movement between plantations was for reasons such as weaning and transfer out to feedlots for finishing, rather than as a result of management response to seasonal change in herbage growth, or on account of wet or dry periods. Hence, it can be concluded that herbage supply-reflected MEB demand was also aseasonal. This is also supported by the fact that the typical weather in Sabah is aseasonal (see Thomas et al., 1976) and that the OPSC subsystems studied did not report a problem of herbage production associated with dry and wet periods. Grinnell et al. (2022) also assumed herbage productivity to be aseasonal in two plantation blocks they studied in West Malaysia.

As noted earlier (see the Results section, Herbage accumulation from 2 month cutting experiments section, above), the perceived aseasonality of herbage production was a justification for annualising the short-term herbage production data collected in August and September 2014. If it can be assumed that herbage accumulation is aseasonal and that there are no major changes in standing herbage mass through the year, then the herbage accumulation data determined by cutting in the months of August and September can be used to infer the annual herbage production, and values so obtained were 6.10 t DM ha^{-1} $year^{-1}$ for 9OP and 2.14 t DM ha^{-1} $year^{-1}$ for 12OP on the OPSC subsystems studied. The validity of the assumption that herbage production is aseasonal could be confirmed in future research.

Elsewhere in tropical areas, the seasonality of herbage production has been reported. At Gowa, South Sulawesi, Indonesia, for example, the herbage supply fluctuated with dry and wet seasons (Bulo et al., 1994). A similar trend was also reported on OPSC systems in the northeastern region of West Malaysia (e.g., Hassan et al., 2004).

Herbage demand during calving and weaning

Under the present farm system operation, there was no seasonal spike in herbage demand on the subsystems during calving and weaning. Superficially, this indicates that calving and weaning were sufficiently spread that they did not create any spike in herbage demand; however, a second possibility is that a spike in demand could have been masked by a fall in cattle body weight. Further research would be needed to determine if this is the case. It would be expected, however, that if the calving rate were higher than the present rate (33%–40%), then the monthly herbage consumption would be increased by lactation and calf-weight-gain energy demand following any periods of concentrated calving. Assuming higher calving rates do occur in future systems, then some aspects of the system will need to be modified. For example, the stocking rate could be lowered accordingly to avoid feed deficit and poor growth of cattle.

Herbage ME and CP

At the time the cattle were transferred to a new paddock, the average herbage ME on 9OP1/9PO2 and 12OP (8.3–8.5 MJ kg^{-1} DM) meets only the minimum requirements for efficient cattle production, but the CP (15%–16% DM) is more than sufficient (Table 5). Similar trends were reported by Grinnell et al. (2022), who gave values of

7.5 MJ kg^{-1} DM for ME and 15.1% for CP in their West Malaysia study and commented that the ME value would restrict animals to 1.6 times maintenance energy intake, which would be less than requirements for lactating animals or animals in late pregnancy. The minimum ME of herbage for cattle production is reported to be 8 MJ kg^{-1} DM (Gobilik, 2017; Smeaton, 2003) and for CP is 6%–8% (Humphreys, 1991). Average herbage ME on 9OP1/9PO2 and 12OP is at the lower end of the range reported for oil palm plantations in Malaysia. The CP is at the upper range. Herbage ME in oil palm plantations in West Malaysia is reported to be 7–10 MJ kg^{-1} DM (Dahlan et al., 1993; Lane & Mustapha, 1983) and CP is reported to be 11%–16%, but sometimes the ME can be as low as 4.6 MJ kg^{-1} DM and the CP as low as 8% (Dahlan et al., 1993; Wattanachant et al., 1997).

In addition to low carbohydrate levels of forage under low light conditions (Dahlan et al., 1993; Samarakoon et al., 1990), the change in functional species composition especially the absence of legumes could also affect forage ME per kilogram DM in oil palm plantations. Broadleaved plants are more nutritious than grasses (Dahlan et al., 1993). Hence, herbage in older oil palm plantations is expected to be of lower ME due to the depletion of broadleaved species and the low production of carbohydrates (by most species) associated with low light intensity at the ground level (Dahlan et al., 1993). Light intensity factors, therefore, may explain the low herbage ME on the subsystems studied. Herbage on the subsystems contained lower numbers of broadleaved species (2–8 species, Supporting Information: Table S1) compared with species numbers reported for other oil palm plantations in Malaysia (e.g., 29–60 species: Chen, 1990; Dahlan et al., 1993).

Nitrogen application, horizontal transfer of N by soil water movement and N uptake by herbage may explain the high herbage CP on the subsystems studied. In oil palm plantations, N fertiliser is applied on the bare soil in a circle of about a 2 m radius around the palm base. However, displacement from that area is common, especially during the rainy season (Bah et al., 2014), and this leads to the fertiliser being unintentionally applied to adjacent herbage. N application improves herbage CP (Chin, 1995; Minson, 1967) and the total N of tropical grasses increases linearly with the incremental supply of N (Johnson et al., 2001). Since N application in mature commercial oil palm plantations (> 5 years old) in Malaysia is reported to be 110–185 kg ha^{-1} $year^{-1}$ (Kee et al., 1995), the low soil N reported for the subsystems studied (see Materials and methods, Farm system detail, section above) must arise from a combination of a high N uptake rate by the oil palms and undergrowth and rainfall-related leaching through the soil profile; however, the low N in the soil could also be due to a suboptimal application of N by the oil palm company as a measure to reduce operation cost.

FCE

The variation in FCE (kg DM kg^{-1} LWG) between the subsystems (CV: 9%–30%) and the most efficient monthly FCE within subsystems (72.3, 28.8 and 27.5 for 9OP1, 9OP2 and 12OP in April, June and May, respectively) appear to be largely a reflection of the numbers of rapidly growing young calves (calves have a higher percentage of total energy for gain compared with adult cattle) in a particular system at a particular time. As mentioned above, relatively, more calves were born in the March–May period. Thus, the high calving and weaning rates in March improved the FCE on the 9OP1 OPSC cow–calf subsystem in April, and the arrival of young calves on 9OP2 and 12OP in March improved FCE on these subsystems in May and June (the weight gain of calves or young cattle increases FCE). On the subsystems, weaning was carried out mainly in March (43 calves) and July (49 calves), with a small number in November (7 calves). However, when the weaning was carried out late and caught up with the arrival of new calves, FCE decreased markedly (Figure 2: November–December, 9OP1), since the number of cattle was higher than the carrying capacity of the undergrowth. The FCE of 9OP2 (weaner bulls) was higher than that of 9OP1 (breeding herd) because in 9OP1, a greater proportion of feed energy was partitioned to body maintenance than to growth, especially by the breeding cows.

Other factors, likely to have an effect on the FCE of the OPSC subsystems, include N application, herbage nutritive value and rainfall. Studies carried out on cut-and-carry feedlot and open-pasture grazing cattle systems (Gobilik, 2017) indicated that N application following rainfall improved FCE (except when *S. sphacelata* 'Kazungula' pasture was being grazed), and this tactical approach to improving response to N fertiliser could also be relevant for OPSC systems. However, a difference between the former and the latter systems is that the N is applied to the oil palms and not to the herbage, which means that the effect of N application on the herbage in OPSC systems is indirect. The relationship between N application, rainfall and FCE, however, could not be specifically explored in this study, as the relevant data had not been recorded in the OPSC systems.

Based on the FCE data, the 9OP1 OPSC cow–calf subsystem (FCE = 94.0 kg DM kg^{-1} LWG) was only half as efficient as an open pasture cow–calf grazing subsystem in Sabah also modelled by MEB (Gobilik, 2017; Brahman Cow–calf subsystem—FCE = 45.3 kg DM kg^{-1} LWG). The difference between the two subsystems is not the result of a difference in cattle breed, since both subsystems were stocked with Brahman cattle imported from Australia. A likely explanation for the differences is in the cow–calf subsystem of the grazing system; the cattle were also fed with the concentrate (PKC) of higher ME content (> 9.5 MJ ME kg^{-1} DM) than the herbage and thus had a greater energy intake and growth per kg of feed consumed. Ibrahim et al. (1987) reported for cattle in Sabah that the growth was only 390 g $head^{-1}$ day^{-1} when feeding solely on herbage, but this improved to 580 g $head^{-1}$ day^{-1} when supplemented with PKC. The average daily gain of cattle in the OPSC subsystems was reported to be 368 g $head^{-1}$ day^{-1} from birth to weaning (average 10 months) and 242 g $head^{-1}$ day^{-1} from weaning to

24 months (see the Materials and methods section, Farm system detail, above), which is in line with the growth reported by Ibrahim et al. (1987) for cattle that feed solely on herbage.

Interpretation of the FCE results for the OPSC cow–calf subsystem in relative to that for the open pasture cow–calf grazing subsystem in Sabah also requires consideration of other factors, especially operational costs and outcomes. Regardless, of the FCE attained, the OPSC cow–calf subsystem studied, and OPSC cattle farming systems generally, requires no expenditure to build and maintain fences and to purchase fertiliser and feed supplement. Fertiliser is applied in the course of normal oil palm production. Beef is produced from herbage that would otherwise be a nuisance or would need to be controlled by herbicide at extra cost but with no return to the oil palm company. A systematic comparison of cost-return and FCE between these systems in Sabah would be a useful future research project. However, the economic benefit of the OPSC farming system was reported in an analysis of OPSC systems in Johor, Malaysia where cattle integration was reported to reduce the total cost of oil palm production by 9% or RM535 ha^{-1} $year^{-1}$ (Gabdo & Abdlatif, 2013). The FCE for the OPSC cow–calf subsystem and open pasture cow–calf grazing system (as stated earlier) was, respectively, 94.0 and 45.3 kg DM kg^{-1} LWG; the feed harvested for the OPSC subsystem was 2.2 t DM ha^{-1} $year^{-1}$ and that for the grazing subsystem was 5.78 t DM ha^{-1} $year^{-1}$, which means 23.4 kg beef ha^{-1} $year^{-1}$ in the OPSC subsystem and 127.6 kg beef ha^{-1} $year^{-1}$ was produced in the grazing subsystem. While, the associated production cost of the same subsystems was, respectively, RM1.41 and RM0.99 per kg of beef produced. Considering this comparison of beef production cost, the benefit of the OPSC cow–calf subsystem appears to be in reducing the oil palm production cost rather than the beef production cost. Thus, there would be merit in the further comparative study of the economics of OPSC and open pasture cow–calf grazing subsystems from the perspective of the cost of increasing the beef production in Sabah; probably, the cost is more when OPSC pastoral systems are intensified, as the cost per kg beef produced of the OPSC cow–calf subsystem is higher.

Implications for future system design

Role of cattle in the plantation

In the oil palm industry, the palms are the main crop, and the OPSC farming system provides understorey vegetation control in the plantations, which otherwise has to be achieved through hand weeding and/or the use of herbicides at a cost while producing beef as a byproduct (Azizol & Norlizan, 2004; Chen, 1990; Devendra & Thomas, 2002). The management of the plantations will always focus on the improvement of fruit and oil yield. For this reason, the use of supplements as feed for the cattle in the OPSC systems is seen as an additional cost, unpractical, and is typically not favoured by plantation managers in Sabah, although the use of supplements was recommended by Grinnell et al. (2022). This interpretation of manager attitude to supplement use is supported by the fact that none of the three subsystems studied used supplements to establish successful OPSC systems. It should be noted, however, that the OPSC cow–calf enterprise also supplies calves to a cut-and-carry feedlot cattle farming system (which could be owned by the same oil palm company), and in the feedlot system, supplements can then be used to improve the cattle growth rate and the profit of the enterprise. If it could be shown that tactical use of supplements in OPSC systems could increase the income from the cattle grazing operation by more than the cost of the supplement, presumably attitudes would change, but at this stage, the evidence for the use of supplements to improve the beef production of OPSC farming systems in Sabah is lacking.

The above analysis of OPSC farming systems in Sabah shows that the objectives of beef production and undergrowth control are not conflicting, but rather complementary, with the successful introduction of an OPSC eliminating a portion of the production cost and delivering a secondary income source. In terms of vegetation control, the data indicate that the stocking rate in 9 year old oil palm plantations could be increased, as herbage production in these plantations is still higher than 2 t DM ha^{-1} $year^{-1}$ and in addition the oil palm manager commented that the ground vegetation in the plantations is not sufficiently controlled. However, it would need to be investigated whether the increased stocking rate for improved understorey vegetation control would compromise cattle growth performance.

Measure of the optimal stocking rate

A previous study of pasture grazing systems in Sabah using this methodology concluded that FCE is sensitive to the stocking rate and declines both above an 'optimal' stocking rate when cattle are underfed and below the optimal stocking rate because herbage quality declines in understocked systems (Gobilik, 2017). As noted above, stocking rate adjustment over time will be required in OPSC systems, because there is a reduction in herbage production with progressive canopy closure (see Dahlan et al., 1993), and optimal stocking rates will differ between individual systems because of local differences in soil, climate, management and other factors. A statistic used in New Zealand dairy farming systems to help farmers determine the optimal stocking rate on individual systems is the 'comparative stocking rate' (CSR: MacDonald et al., 2008; Penno, 1999) defined as kg animal liveweight ha^{-1} $year^{-1}$ divided by tonnes total feed DM offered ha^{-1} $year^{-1}$. In New Zealand dairy systems, the optimal CSR is generally accepted as lying within the range of 85–100 kg cow liveweight per tonne annual feed supply. Similar values to those from New Zealand appeared to apply in cut-and-carry and grazing beef production systems in Sabah (Gobilik, 2017).

A CSR calculated for the OPSC cow–calf subsystem (9OP1), for example, is 89 kg LWT t^{-1} DM (if the feed offered is taken as the average feed harvested in the system, which is 2.2 t DM ha^{-1} $year^{-1}$, plus a 15%

allowance for nonutilisation) or a stocking rate of approximately 231 kg cattle LWT ha^{-1}. The CSR estimates reported by Gobilik (2017) for near-optimal stocking for an open-pasture grazing system were 94 kg LWT t^{-1} DM and for a cut-and-carry feedlot system 96 kg LWT t^{-1} DM. Comparing these three CSRs, it appears that the CSR of the OPSC cow–calf subsystem is lower, indicating that the subsystem might be understocked, which is similar to the view of Grinnell et al. (2022). We suggest, therefore, that if a method to determine herbage productivity (as distinct from herbage consumption, estimated by MEB) could be developed, then perhaps a CSR-type statistic will be useful for farmers and extension officers in Sabah to explore how to lift the performance of OPSC farming systems as in the examples above from cut-and-carry feedlot and grazing cattle farming systems in Gobilik (2017).

CONCLUSIONS

Based on the data analyses above:

- The 9 year old oil palm plantations (9OP1 and 9OP2 OPSC subsystems) were supplying 2.0–2.4 t DM ha^{-1} year^{-1} of herbage and a 12 year old oil palm plantation (12OP OPSC subsystem) was supplying 1.4–1.7 t DM ha^{-1} year^{-1} for beef production. These values are higher than those previously reported in Malaysia for oil palm plantations of similar age.
- The cattle production of the system was constrained by a marginal herbage ME value of 8.3–8.5 MJ kg^{-1} DM. However, this value is higher than values previously reported in OPSC systems. Meanwhile, the CP value of herbage in the systems studied (15%–16% DM) should support moderate levels of cattle production.
- In current practice, calving in the system is distributed throughout the year though somewhat concentrated in the months of March–May and August–October. There was no seasonal spike in feed demand linked to calving and lactation observed in the data. Further study is required to identify ways to coordinate both calving and weaning events so that the stocking rate relative to herbage growth is optimal and FCE remains as high as possible for a given system.
- Breeding systems producing calves have an intrinsically lower FCE than systems where calves are reared. However, for any given OPSC system, monitoring FCE over a complete 12 months for different oil palm ages is necessary to identify opportunities to increase efficiency. This dimension has been lacking in most previous studies.
- The study provides benchmark feed supply data for planning stocking rates when introducing cattle to oil palm plantations in Sabah. In future research, the level of the stocking rate relative to herbage growth could be quantified in a CSR-type statistic, as used in the New Zealand dairy industry, as a tool to assist plantation managers to optimise FCE to improve beef production. However, such a tool would require the development of a methodology to assess herbage productivity independently of MEB calculations.

AUTHOR CONTRIBUTIONS

Januarius Gobilik: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; writing—original draft; writing—review and editing. **Hasbudie Baco**: Project administration; resources. **Mohd. Azid Kabul**: Resources. **Suhaimi Dollah**: Resources. **Stephen T. Morris**: Supervision; writing—review and editing. **Cory Matthew**: Resources; supervision; writing—review and editing.

ACKNOWLEDGEMENTS

The authors thank the staff of the Department of Veterinary Services, West Malaysia for analysing the herbage samples for ME, CP and nutritive values. This study was supported by a PhD scholarship and internal research grants (GKP0019-STWN-2016 and SDK0010-2017) to J. G. from the Government of Malaysia through Universiti Malaysia Sabah and the Ministry of Higher Education of Malaysia.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data presented in this study are available within the article and the supplementary data that support the results will be available from the corresponding author upon reasonable request.

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REFERENCES

Ayob, M. A., & Kabul, M. A. (2009). Cattle integration in oil palm plantation through systematic management. In *Proceedings of the 1st International Seminar on Animal Industry (pp. 66–73), Bogor (Indonesia), 23–24 November 2009*. Retrieved December 16, 2022, from https://fapet.ipb.ac.id/~isai/pdf/Prosiding_ISAI_1_2009.pdf

Azhar, B., Tohiran, K. A., Nobilly, F., Zulkifli, R., Syakir, M. I., Ishak, Z., Razi, N., Oon, A., Shahdan, A., & Maxwell, T. M. R. (2021). Time to revisit oil palm-livestock integration in the wake of united nations sustainable development goals (SDGs). *Frontiers in Sustainable Food Systems*, *5*, 640285. https://doi.org/10.3389/fsufs.2021.640285

Azizol, M. S., & Norlizan, M. N. (2004). Beef cattle farming as a new technology forthe oil palm industry. In R. A. Halim, N. R. A. Hamid, & S. M. Nasir (Eds.), *Forages and feed resources in commercial livestock production systems* (pp. 31–35). Proceedings of the eight Meeting of The Regional Working Group on Grazing and Feed Resources for Southeast Asia, Kuala Lumpur, Malaysia, 22–28 September 2003. MARDI, Ministry of Agriculture and Agro-based Industries, Malaysia. 212pp.

Bah, A., Husni, M. H. A., Teh, C. B. S., Rafii, M. Y., Syed Omar, S. R., & Ahmed, O. H. (2014). Reducing runoff loss of applied nutrients in oil palm cultivation using controlled-release fertilizers. *Advances in Agriculture*, *2014*, 1–9. https://doi.org/10.1155/2014/285387

Baldocchi, D., Matt, D., Hutchison, B., & McMillen, R. (1984). Solar radiation within an oak–hickory forest: An evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods. *Agricultural and Forest Meteorology*, *32*, 307–322. https://doi.org/10.1016/0168-1923(84)90056-X

Bremer, J. A., de Bruyn, L. A. L., Smith, R. G. B., & Cowley, F. C. (2022). Knowns and unknowns of cattle grazing in oil palm plantations: A review. *Agronomy for Sustainable Development*, *42*, 17. https://doi.org/10.1007/s13593-021-00723-x

Bremer, J. A., de Bruyn, L. A. L., Smith, R. G. B., Darsono, W., Soedjana, T. D., & Cowley, F. C. (2022). Prospects and problems: Considerations for smallholder cattle grazing in oil palm plantations in South Kalimantan, Indonesia. *Agroforestry Systems*, *96*, 1023–1037. https://doi.org/10.1007/s10457-022-00759-2

Bulo, D., Blair, G. J., Till, A. R., & Stür, W. (1994). Yield and digestibility of forages in East Indonesia II. Grasses. *Asian-Australasian Journal of Animal Sciences*, *7*(3), 335–342. https://doi.org/10.5713/ajas.1994.335

Chacon, E., & Stobbs, T. (1976). Influence of progressive defoliation of a grass sward on the eating behaviour of cattle. *Australian Journal of Agricultural Research*, *27*, 709–727. https://doi.org/10.1071/AR9760709

Chen, C. P. (1990). Cattle productivity under oil palm in Malaysia. In H. M. Shelton & W. W. Stür (Eds.), *Forages for plantation crops* (pp. 97–101). Proceedings of a workshop, Sanur Beach, Bali, Indonesia 27–29 June, 1990. ACIAR Proceedings No. 32, 168pp. https://www.aciar.gov.au/publication/technical-publications/forages-plantation-crops

Chin, F. Y. (1995). Critical pasture management and utilisation to reduce feed supplementation. *Enhancing sustainable livestock-crop production in smallholder-farming systems*. Proceedings of the fourth meeting of Regional Working Group on Grazing and Feed Resources of Southeast Asia, 20–24 March 1995, Nha Trang, Vietnam, 251pp.

Cooper, J. P. (1970). Potential production and energy conversion in temperate and tropical grasses. *Herbage Abstracts*, *40*, 1–15.

Dahlan, I., Yamada, Y., & Mahyuddin, M. D. (1993). Botanical composition and models of metabolizable energy availability from undergrowth in oil palm plantations for ruminant production. *Agroforestry Systems*, *24*, 233–246. https://doi.org/10.1007/BF00705624

Descals, A., Wich, S., Meijaard, E., Gaveau, D. L. A., Peedell, S., & Szantoi, Z. (2021). High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. *Earth System Science Data*, *13*, 1211–1231. https://doi.org/10.5194/essd-13-1211-2021

Devendra, C., & Thomas, D. (2002). Crop–animal interactions in mixed farming systems in Asia. *Agricultural Systems*, *71*, 27–40. https://doi.org/10.1016/S0308-521X(01)00034-8

DOA. (2015). *Laporan Taburan Hujan 2008–2012*. Department of Agriculture Sabah. http://ww2.sabah.gov.my/tani/s4_mak_pertanian/maklumat_pertanian.html

Dohi, H., Yamada, A., & Entsu, S. (1991). Cattle feeding deterrents emitted from cattle feces. *Journal of Chemical Ecology*, *17*, 1197–1203. https://doi.org/10.1007/BF01402943

DOSM. (2021). *Supply and utilization accounts: Selected agricultural commodities, Malaysia 2016–2020*. Department of Statistics Malaysia. https://www.dosm.gov.my/

Gabdo, B. H., & Abdlatif, I. B. (2013). Analysis of the benefits of livestock to oil palm in an integrated system: Evidence from selected districts in Johor, Malaysia. *Journal of Agricultural Science*, *5*, 47–55. https://doi.org/10.5539/jas.v5n12p47

Germer, J. (2003). *Spatial undergrowth species composition in oil palm (Elaeis guineensis Jacq.) in West Sumatra* [Doctoral dissertation]. University of Hohenheim, Germany. https://opus.uni-hohenheim.de/volltexte/2003/42/pdf/Spatial_undergrowth_species_composition_in_oil_palm.pdf

Gobilik, J. (2017). *Considerations of feed demand and supply for the evolution and expansion of beef cattle farming in Sabah, East Malaysia* [Doctoral dissertation]. Massey University, Palmerston North, New Zealand. https://mro.massey.ac.nz/handle/10179/11855

Gobilik, J., Adam, L., Abdullah, P., Abas, H., Morris, S. T., Matthew, C., & Yeo, B. K. (2017). Correlations between feed conversion efficiency, rainfall, nitrogen (N) application and mobilised body energy (ME_{LWL}) of a cut-and-carry feedlot cattle farming system at SPT 16 Tawau, Sabah and implications for feedlot nutrient management. *Transactions on Science and Technology*, *4*, 76–83. https://tost.unise.org/pdfs/vol4/no2/4x2x76x83.pdf

Gobilik, J., Morris, S. T., & Matthew, C. (2021). Evolution in configuration and productivity of New Zealand Hill Country sheep and beef cattle systems. *Agriculture*, *11*, 531. https://doi.org/10.3390/agriculture11060531

Grinnell, N. A., van der Linden, A., Azhar, B., Nobilly, F., & Slingerland, M. (2022). Cattle-oil palm integration—A viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability. *Livestock Science*, *259*, 104902. https://doi.org/10.1016/j.livsci.2022.104902

Hassan, A. W. (2001). Forages in oil palm and rubber plantations in Malaysia. In F. A. Moog, S. G. Reynolds, & K. Maaruf (Eds.), *Forage development in Southeast Asia: Strategies and Impacts*. Proceedings of the seventh Meeting of The Regional Working Group on Grazing and Feed Resources, Food and Agriculture Organization of the United Nations and University of Sam Rapulangi, Indonesia. http://www.fao.org/ag/agp/agpc/doc/Proceedings/manado/cover.html

Hassan, A. W., Aminah, A., & Mohd. Ariff, O. (2004). The changes in pasture availability and botanical composition under oil palm-cattle integration at Gua Musang, Kelantan. In R. A. Halim, N. R. A. Hamid, & S. M. Nasir (Eds.), *Forages and feed resources in commercial livestock production systems* (pp. 52–55). Proceedings of the eight Meeting of The Regional Working Group on Grazing and Feed Resources for Southeast Asia, Kuala Lumpur, Malaysia, 22–28 September 2003. MARDI, Ministry of Agriculture and Agro-based Industries, Malaysia, 212pp.

Humphreys, L. R. (1991). *Tropical pasture utilization*. Cambridge University Press. https://doi.org/10.1017/CBO9780511525810

Ibrahim, M., Awang Salleh, A. S., & Chew, C. T. (1987). *Utilization of PKC and its implication to the cattle industry in Sabah*. Paper presented of SASS Seminar on Palm Kernel Utilization and Recent Advances in Cocoa Cultivation, June 11–13, Marco Polo Hotel, Tawau, Department of Veterinary Services and Animal Industry, Sabah, 13pp.

Jalaludin, S., & Halim, R. A. (1998). Development of the livestock industry in Malaysia. In Y. W. Ho & Y. K. Chan (Eds.), *Proceedings of the Regional Workshop on Area-Wide Integration of Crop-Livestock Activities* (Vol. 1998, pp. 18–20). FAO Regional Office Bangkok Thailand.

Johnson, C. R., Reiling, B. A., Mislevy, P., & Hall, M. B. (2001). Effects of nitrogen fertilization and harvest date on yield, digestibility, fiber, and protein fractions of tropical grasses. *Journal of Animal Science*, *79*, 2439–2448. https://doi.org/10.2527/2001.7992439x

Kabul, M. A. (2008). Successful development of a model for cattle integration in Sawit Kinabalu. *Planter*, *84*, 813–819.

Kartini, S., Awang Sufiyan, A. H., Dayou, J., Zul Hilmey, M. M., & Sani, M. S. (2015). Measurement of global solar radiation in Kota Kinabalu, Sabah Malaysia. *ARPN Journal of Engineering and Applied Sciences*, *10*, 6467–6471.

Kee, K. K., Goh, K. J., & Chew, P. S. (1995). Effects of NK fertiliser on soil pH and exchangeable K status on acid soils in an oil palm plantation in Malaysia. *Developments in Plant and Soil Sciences*, *64*, 809–815. https://doi.org/10.1007/978-94-011-0221-6_130

Khasanah, N., van Noordwijk, M., Slingerland, M., Sofiyudin, M., Stomph, D., Migeon, A. F., & Hairiah, K. (2020). Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. *Frontiers in Sustainable Food Systems*, *3*, 122. https://doi.org/10.3389/fsufs.2019.00122

Lam, M. K., Tan, K. T., Lee, K. T., & Mohamed, A. R. (2009). Malaysian palm oil: Surviving the food versus fuel dispute for a sustainable future. *Renewable and Sustainable Energy Reviews*, *13*, 1456–1464. https://doi.org/10.1016/j.rser.2008.09.009

Lambert, M. G., & Litherland, A. J. (2000). A practitioner's guide to pasture quality. *Proceedings of the New Zealand Grassland Association*, *62*, 111–115. https://doi.org/10.33584/jnzg.2000.62.2383

Lane, I. R., & Mustapha, M. (1983, August 14–19). Utilisation of natural pastures for dairy cattle in humid tropics. *Paper presented to Fifth World Conference on Animal Production* (p. 2). Tokyo, Japan.

Latif, J., & Mamat, M. N. (2002). A financial study of cattle integration in oil palm plantations. *Oil Palm Industry Economic Journal*, *2*, 34–44.

MacDonald, K. A., Penno, J. W., Lancaster, J. A. S., & Roche, J. R. (2008). Effect of stocking rate on pasture production, milk production and reproduction of dairy cows in pasture-based systems. *Journal of Dairy Science*, *91*, 2151–2163. https://doi.org/10.3168/jds.2007-0630

Minson, D. J. (1967). The voluntary intake and digestibility, in sheep, of chopped and pelleted *Digitaria decumbens* (pangola grass) following a late application of fertilizer nitrogen. *British Journal of Nutrition*, *21*, 587–597. https://doi.org/10.1079/BJN19670062

Murphy, D. J., Goggin, K., & Paterson, R. R. M. (2021). Oil palm in the 2020s and beyond: Challenges and solutions. *CABI Agriculture and Bioscience*, *2*, 39. https://doi.org/10.1186/s43170-021-00058-3

Naylor, R. L., Higgins, M. M., Edwards, R. B., & Falcon, W. P. (2019). Decentralization and the environment: Assessing smallholder oil palm development in Indonesia. *Ambio*, *48*, 1195–1208. https://doi.org/10.1007/s13280-018-1135-7

Nicol, A. M., & Brookes, I. M. (2007). The metabolisable energy requirements of grazing livestock. In P. V. Ratray, I. M. Brookes, & A. M. Nicol (Eds.), *Pasture and supplements for grazing animals* (Vol. 14, pp. 151–172). New Zealand Society of Animal Production, Occasional Publication.

Parveez, G. K. A., Kamil, N. N., Zawawi, N. Z., Ong-Abdullah, M., Rasuddin, R., Loh, S. K., Selvaduray, K. R., Hoong, S. S., & Idris, Z. (2022). Oil palm economic performance in Malaysia and R&D progress in 2021. *Journal of Oil Palm Research*, *34*, 185–218. https://doi.org/10.21894/jopr.2022.0036

Parveez, G. K. A., Tarmizi, A. H. A., Sundram, S., Loh, S. K., Ong-Abdullah, M., Palam, K. D. P., Salleh, K. M., Ishak, S. M., & Idris, Z. (2021). Oil palm economic performance in Malaysia and R&D progress in 2021. *Journal of Oil Palm Research*, *33*, 181–214. https://doi.org/10.21894/jopr.2021.0026

Penno, J. W. (1999). Stocking rate for optimum profit. *New Zealand, South Island Dairy Event 1* (pp. 25–43). Lincoln University and Dexcel.

Samarakoon, S. P., Wilson, J. R., & Shelton, H. M. (1990). Growth, morphology and nutritive quality of shaded *Stenotaphrum secundatum*, *Axonopus compressus* and *Pennisetum clandestinum*. *The Journal of Agricultural Science*, *114*, 161–169. https://doi.org/10.1017/S0021859600072154

SKSB. (2010). *Annual Report of Sawit Kinabalu Sendirian Berhad (2010)*. Kota Kinabalu, Sabah. http://www.sawitkinabalu.com.my/wp-content/uploads/2012/02/AR2010.pdf

SKSB. (2022). Sawit Kinabalu Sendirian Berhad: Livestock cattle integration. https://www.sawitkinabalu.com.my/index.php/livestock/

Smeaton, D. (2003). Nutritional requirements for beef cattle. In D. C. Smeaton (Ed.), *Profitable beef production* (pp. 28–37). New Zealand Beef Council.

Thomas, P., Lo, F. K. C., & Hepburn, A. J. (1976). *The land capability classification of Sabah, Volume 1 (the Tawau Residency), 2 (the Sandakan Residency), 3 (the West Coast and Kudat Residencies) and 4 (the Interior Residency and Labuan)*. Land Resources Division, Ministry of Overseas Development, Tolworth Tower, Surbiton. Retrieved December 16, 2022, from https://edepot.wur.nl/479776,/487019,/487018,%20and/487017 for Volume 1, 2, 3 and 4, respectively.

Tohiran, K. A., Nobilly, F., Zulkifli, R., Ashton-Butt, A., & Azhar, B. (2019). Cattle-grazing in oil palm plantations sustainably controls understory vegetation. *Agriculture, Ecosystems & Environment*, *278*, 54–60. https://doi.org/10.1016/j.agee.2019.03.021

Wahab, S. A., Tohiran, K. A., Rahman, A. K. A., & Taib, H. M. (2021). The adaptability of smallholders toward livestock integration with oil palm and income generated. *Jurnal Penyelidikan Sains Sosial (JOSSR)*, *4*, 67–78.

Wattanachant, C., Dahlan, I., Zulkifli, A., & Rajion, M. A. (1997). Sheep-oil palm integration: Growth performance of dorset × malin and dorset × siamese long tail sheep. *Pertanika Journal of Tropical and Agricultural Science*, *20*, 169–177.

Wilson, J. R., & Ludlow, M. M. (1990). The environment and potential growth of herbage under plantations. In H. M. Shelton & W. W. Stür (Eds.), *Forages for plantation crops* (pp. 10–24). Proceedings of a workshop, Sanur Beach, Bali, Indonesia. 27–29 June, 1990. ACIAR Proceedings No. 32, 168pp. https://www.aciar.gov.au/publication/technical-publications/forages-plantation-crops

Wong, C. C. (1998). Soil compaction under cattle grazing in oil palms. *Journal of Tropical Agriculture and Food Science*, *26*, 203–210.

Zamri-Saad, M., & Azhar, K. (2015). Issues of ruminant integration with oil palm plantation. *Journal of Oil Palm Research*, *27*, 299–305.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Gobilik, J., Baco, H., Kabul, M. A., Dollah, S., Morris, S. T., & Matthew, C. (2023). Feed profile analysis of oil palm-integrated beef cattle farming systems by metabolic energy budgeting and implications for beef production and pastoral system design. *Grassland Research*, *2*(1), 56–68. https://doi.org/10.1002/glr2.12044