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Cattle-oil palm integration – a viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability

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HIGHLIGHTS

- We studied the species composition in the undergrowth of an oil palm plantation
- The undergrowth provided ample crude protein to cattle, but energy may be limiting
- Current stocking densities may be increased without exceeding carrying capacity
- Integrating palm oil and cattle reduces costs and increases resource use efficiency

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ABSTRACT

Palm oil production in Malaysia contributes significantly to the national economy, but its production has adverse effects on the environment. A solution to mitigate environmental impacts and increase resource use efficiency is integrating palm oil and beef cattle production. This can reduce deforestation, needs for grazing land, and reduce herbicide use in plantations when cattle graze the weeds. Integration is more complex if the plantation and cattle are owned by different parties, as plantation owners indicate they perceive little or no benefit from integration. As a result, plantation managers consider the undergrowth as weeds and do not aim at improving the nutritional quality and biomass. This disinterest may explain why the potential of the undergrowth as forage has been understudied. The first objective of this study was, therefore, to assess the nutritional quality of the undergrowth in an integrated oil palm-cattle system where cattle are owned by smallholder farmers. The second objective was to estimate to what extent the nutritional requirements of cattle grazing the undergrowth are met. Plant species composition was determined and biomass was measured in an oil palm plantation in Peninsular Malaysia. Furthermore, the cattle diet was estimated from observations during grazing and interviews with five smallholder farmers were conducted. The species with the highest biomass in the undergrowth were *Ottochloa nodosa, Axonopus compressus, Cyrtococcum oxyphyllum, Arthraxon hispidus*, and *Adiantum latifolium*. Cattle selected for the more nutritious species within the available biomass. The grass *A. compressus* (64 %) and pruned oil palm fronds (18%) made up most of the cattle's diet, and the leguminous cover crop *Pueraria phaseoloides* was preferred if present. The diet contained 151 g crude protein (CP) kg^{-1} DM, and the ME content was 7.5 MJ ME kg^{-1} DM. The nutritional quality was estimated to cover energy requirements of cattle for maintenance by 1.6 times, whereas it provided ample CP. These results suggest that energy requirements may not always be fully met. Energy deficiency could be mitigated by feeding cattle with palm kernel meal, an energy-rich by-product from palm kernel oil production. Cattle were kept at or above the recommended stocking density for Malaysian plantations (0.11 TLU ha^{-1}). Our observations suggest that the carrying capacity of the undergrowth is higher than the recommended stocking density, which implies scope to increase stocking densities and beef production, thereby

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reducing the need for further deforestation. In conclusion, integrating palm oil and cattle production is a viable strategy for both smallholders and plantation management to increase resource use efficiency in plantations and beef self-sufficiency in Malaysia.

1. Introduction

Malaysia is, after Indonesia, the world's second-largest palm oil producer, responsible for approximately 39 % of global palm oil production. In 2019, Malaysia produced nearly 20 million t crude palm oil (CPO) and exported more than 18.4 million t CPO (MPOC, 2021). Consequently, the Malaysian palm oil sector not only acts as a key driver of the country's agricultural industry but also contributes significantly to the national economy (Ferdous Alam et al., 2015).

Despite its contribution to the Malaysian economy, the palm oil industry is highly contested. Palm oil production resulted in the loss of biodiversity due to the expansion of plantations into cleared forests and the vast use of herbicides for weed control (Ferdous Alam et al., 2015; Tohiran et al., 2017). Further, the expansion of oil palm plantations at the cost of native rain forests contributes significantly to global greenhouse gas emissions via natural and intentional forest fires, drainage of peat soils, and a reduced atmospheric CO_2 absorption capacity of oil palm compared to native forests (Russel, 2018). The Malaysian government is required to prevent further replacement of native forests by oil palm plantations to comply with multiple international demands and agreements regarding climate action, such as the FAO's sustainable development goals (Rosa, 2017), the Roundtable on Sustainable Palm Oil (RSPO), the government initiative Malaysian Sustainable Palm Oil (Kuntom, 2003) and the Paris Agreement.

Further, the Malaysian government has been striving for years to increase national beef self-sufficiency up to 50 % (Government of Malaysia, 2015). The demand for meat is expected to rise to up to 1.8 million t y^{-1}, which the livestock sector is currently unable to provide (Nor & Rosali, 2014). While the pig and poultry sectors are well developed, ruminant production systems in Malaysia predominantly occur in smallholder settings, lacking competitiveness in the global market. Apart from high feed prices and the lack of quality breeds, expertise, and workers, smallholder productivity is limited by diseases, land scarcity, and the resulting competition for grazing land (Latif & Mamat, 2002; Nor & Rosali, 2014).

A strategy to increase both the national beef self-sufficiency and the environmental sustainability of the palm oil sector is integrating beef and palm oil production, where cattle graze on the oil palm undergrowth (Azhar et al., 2017, 2021; Latif and Mamat, 2002; Tohiran et al., 2019a). Integrated livestock-oil palm production systems have existed in Malaysia since the late 1980s, as a method to maximize revenues from livestock and palm oil production, while simultaneously optimizing resource use (Awaludin, 1999; Gabdo et al., 2014; Sudaryanto, 2017). The literature reports multiple synergies that emerge from integrating beef and oil palm production. If properly managed, grazing increases ecosystem functioning, leading to increased soil nutrient contents and enhanced soil structure and hydrological properties such as increased water infiltration, porosity, and soil moisture (Slade et al., 2014). Organic fertilization from animal manure can positively affect soil organic matter and increase fresh fruit bunch (FFB) yield (Devendra, 2011). Grazing of highly palatable bagworm-promoting plant species can contain pest outbreaks (Awaludin, 1999). Weeding and labor costs decrease due to grazing cattle (Ayob, 2009). In a study with smallholders in Malaysia, livestock integration decreased weeding and labor costs by 8% while simultaneously increasing FFB yield by 14 %, and increasing the total revenue of the enterprise by 15 % (Gabdo & Abdlatif, 2013). Tree canopies allow sufficient light penetration, enabling an undergrowth dry matter yield of 500 kg ha^{-1} y^{-1} with adequate nutritional quality, while simultaneously providing shade for the cattle (Ayob, 2009; Suteky, 2009). Other studies confirmed also that plants in the oil palm undergrowth are generally of sufficient nutritional value for ruminants (Gabdo & Abdlatif, 2013; Sudaryanto, 2017). One study reports cattle grazing the undergrowth in integrated systems showed average daily weight gains of 250 g to 300 g (Latif & Mamat, 2002).

Notwithstanding the synergies, concerns from plantation owners have prevented the emergence of the integrated system into standard practice to date (Silalahi et al., 2018). Foremost, plantation management fears losses in profit due to distractions and collisions between livestock farming and the main plantation business (Ayob, 2009). Further, improperly managed free-roaming cattle are considered a threat to the plantation business, as cattle feed on palm fronds and harvested fruit bunches. In a study by Latif & Mamat (2002) on cattle integration in mature oil palm plantations, however, no negative effect on FFB yield was identified. Trees older than seven years were found suitable for grazing cattle, as palm fronds and fruit bunches were out of reach.

These concerns are likely to be intensified in integrated systems where cattle are owned by smallholder farmers. In such systems, plantation owners may perceive benefits to be rather for the smallholders than for the plantation. The objective of undergrowth management in oil palm plantations is primarily weed control, and undergrowth composition and nutritional quality are merely unintended results (Ayob, 2009). As a result, the plantation management may be less inclined to account for the nutritional quality of the undergrowth in weeding practices and to sow cultivated feed or cover crops in the undergrowth. Hence, the nutritional quality may be lower if cattle are owned by smallholders. The limited literature on the nutritional quality of the undergrowth and beef production, however, mainly focuses on integrated systems where cattle are owned and managed by the plantation.

The nutritional quality of the oil palm undergrowth is known to differ greatly between locations, depending on general agroecological circumstances and whether the undergrowth consists of naturally growing weeds or intentionally cultivated feed and cover crops (Silalahi et al., 2018). Further, most studies (Dahlan et al., 1993; Dahlan & Wahab, 2014; Samedani et al., 2014; Suteky, 2016) analyze the entire standing biomass but none look at cattle's selection within the biomass to analyze the actual cattle diets.

Given the absence of standard practice, the mentioned location specificity of vegetation composition and biomass, and the absence of studies that look at preferred cattle diets, this study assessed the nutritional quality and cattle production in an integrated oil palm-cattle system where cattle belonged to independent smallholders instead of the plantation, and undergrowth composition and grazing patterns were not affected by the plantation. While personal testimonies of smallholder farmers suggest that cattle grazing on the undergrowth of plantations perform well and that cows calve each year, such narratives have not been confirmed scientifically. Thus, it was further investigated whether the quantity and quality of oil palm undergrowth are sufficient to support the maintenance, growth, and reproduction of beef cattle. To this end, dominant plant species and those preferred by grazing cattle were identified in the undergrowth of an industrial palm oil plantation in Peninsular Malaysia. The nutritional quality of relevant species was assessed along with the energy and protein requirements of cattle. Based on the defined nutritional quality, biomass availability, and cattle requirements, the scope to increase beef production and stocking density was assessed. Comparing current stocking densities with feed availability and composition was used as an indicator of production level and the system balance.

2. Materials and methods

The study was conducted at an oil palm plantation in the state of Negeri Sembilan in Peninsular Malaysia, in the district of Pedas. The oil palm plantation comprises two divisions, one main estate of 437 ha (D1) and one smaller division of 87 ha (D2, Table 1). Both divisions have mature and immature palm trees. The estate name and geographical coordinates remain concealed upon request of the plantation. The climate at the study site is classified as Af (tropical rainforest) according to the Köppen-Geiger classification system, with an average annual rainfall of 2021 mm (Appendix 1) and an average temperature of 27.1°C. There are wetter and dryer months, with a maximum difference of 134 mm precipitation (Climate-Data.org, 2021). The study was conducted during the wetter season, in October and November 2019. Within a year, temperatures and vegetation growth vary to a small degree. Therefore, no difference in vegetation growth between the wetter and drier season is expected. The predicted most dominant class of soil in the Pedas district are Ultisols, according to the USDA taxonomy system (USDA, 1999; Appendix 2).

The plantation structure follows a standardized planting scheme (Fig. 1). Trees are planted in a triangular arrangement with a distance of 8.80 m between every tree. The planting density is 144 trees per ha in 8 rows of 18 palm trees. In every other row there is a harvesting path of 3.70 m in width. The tree trunk diameter is approximately 0.5 m. The area surrounding the tree trunk is treated with herbicides and frequently mechanically cleared in a 2.40 m radius for palm protection as well as facilitating harvesting.

Two student research assistants were provided by the Universiti Putra Malaysia (UPM) to act as interpreters to facilitate communication, to function as assistants during data collection, and as guides to navigate throughout the plantation.

Interviews were conducted with the five livestock farmers that keep cattle (n = 4 farmers) and buffalo (n = 1 farmer) on the plantation premises. The questioning was done in individual appointments over two weeks in October 2019. All interviews were conducted in Malay or Tamil. Translation to and from English was done by the UPM research assistants.

2.1. On-site cattle grazing management

The arrangement to allow livestock of five farmers into the plantation is historically grown, unofficial, and strictly verbal. The integration is non-systematic, meaning that livestock ranges freely around the plantation, and grazing decisions are made ad hoc by livestock farmers. There are no fences or grazing management schemes. Livestock farmers are frequently informed about areas that are restricted due to replanting or application of chemicals. However, plantation activities, such as fertilizer and herbicide treatments, are not adapted to potential effects on the livestock such as in systematic integration (Awaludin, 1999; Tohiran et al., 2017). A total of 189 heads of cattle, predominantly Kedah Kelantan, and 60 Malaysian swamp buffalos grazed on 437 ha in D1, while 20 heads of cattle grazed on 87 ha in D2 (Appendix 3).

Table 1
Labels of quarters the oil palm plantation divisions were subdivided in, and quarter size in ha.

division 1		division 2	
quarter label	size in ha	quarter label	size in ha
Northeast (NE)	104	North (N)	21
Northwest (NW)	113	Central (C)	23
Southeast (SE)	114	Southeast (SE)	20
Southwest (SW)	126	Southwest (SW)	20

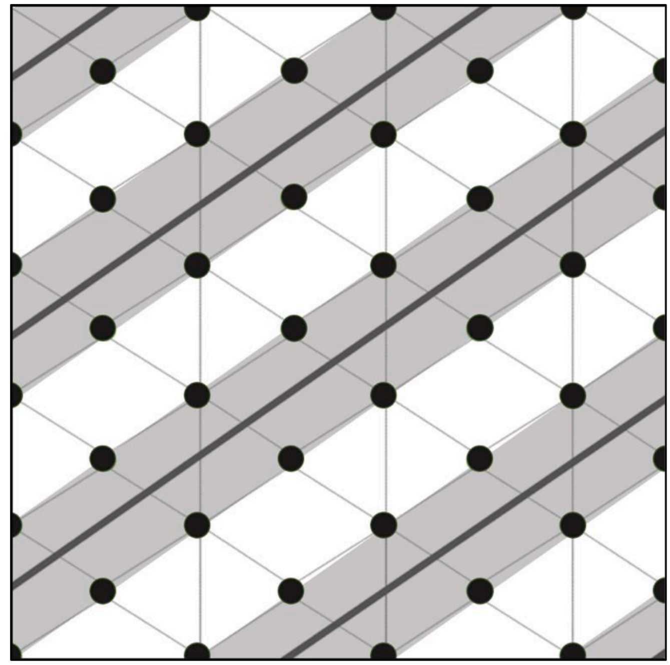

Fig. 1. Schematic depiction of the oil palm planting scheme at the study plantation in Negeri Sembilan, Malaysia. Palm trees (dots) are planted in equilateral triangles (thin grey lines), forming harvesting paths (grey fields with thick black lines) and inter-row areas (white fields).

2.2. Undergrowth composition assessment

Plant species in the plantation undergrowth were sampled according to the quadrat method as described by Baxter (2014) and Fidelibus (1993), with a quadrat size of 0.5 m^2 as proposed by Dahlan et al. (1993) that was better suited to the undulating landscape in the plantation. For plant sampling, the two plantation divisions were each divided into four quarters of similar size (Table 1). The borders of each quarter are in line with natural borders such as paths, paved roads, and rivers, as well as soft borders induced by differences in tree age or the terrain. Three distinguished strata were determined: harvesting path (HP), inter-row (IR), and tree trunk diameter (TTD). Exploitation, treatment, and plant population were expected to differ between these strata. Due to the frequent treatment of the TTD with herbicides, the mechanical clearing of the area for harvesting, and the resulting lack of weed growth, the TTD was not included in plant sampling.

In D1, a total of 48 quadrats were sampled, 6 per stratum (HP and IR) in each quarter. In D2, a total of 24 quadrats were sampled, 3 per stratum in each quarter. A random starting point was chosen within each quarter and stratum, in an area where animals were previously observed when grazing. The second and third quadrats were placed at a 50 m distance to the first and second quadrat, following a straight line within the respective quarter and stratum.

In every quadrat, the occurring plant species were identified using a pictorial guide to common weeds of plantations (Chung et al., 2017) and the smartphone application "Pl@ntNet"(Cirad-France, Version 3.0). Identified plant species were later verified via online searches. Then all individuals of each species in a quadrat were counted. The relative density of each species detected in a quadrat was then calculated as the count of all individuals of the same species relative to the total plant count in the respective quadrat.

Further, the dry matter (DM) weight of each species was assessed via harvesting all aboveground biomass in the quadrat at 1.5 cm height, separated by species Dahlan et al. (1993). The fresh plant material was weighed immediately after harvesting, using a scale with a precision of 0.5 g. Due to the low precision of the weighing scale and the resulting error probability, plant samples with a fresh matter (FM) weight below 1.5 g were excluded from the biomass assessment. After harvest, plant samples were dried first by sunlight for 4 days and then in an oven at 75°C for 48 h, as suggested by Wibawa et al. (2009). Subsequently, the DM was weighed using a laboratory scale with a precision of 0.01 g.

To measure the sward height, a wooden rule of 100 cm length with 1 mm gradations was held vertically and the height of the first piece of green, non-flowering vegetation was read on the rule and then noted (Stewart et al., 2001). Within each quadrat, sward height was measured in 5 locations, resembling an X-shape, and from this, the average quadrat sward height was calculated. Further, ground coverage was measured using the mobile phone app “Canopeo” (Oklahoma State University, Version 2.0).

The relative dominance of each species was calculated as the DM weight of a species relative to the total DM weight in a quadrat. The frequency of a species was calculated as the ratio of quadrats containing the respective species to the overall total number of sampled quadrats in both divisions. The total relative density of each species was calculated as the ratio of the total counted individuals of the same species to all counted individuals, over all sampled quadrats in both divisions (Appendix 4). Similarly, the total relative dominance of each species was calculated as the ratio of the total collected DM of a species to all collected biomass over all sampled quadrats. Finally, the sum dominance ratio (SDR) was calculated for each species according to Eq. 1 (Eq. 1, Wibawa et al., 2009), to determine the major species. Further, the total harvested DM per quadrat was calculated for assessment of average DM biomass per ha in the plantation undergrowth. Where SDR is the species sum dominance ratio and sp. is the species.

$$\text{SDR sp.x} = (\textit{frequency} + \textit{total relative dominance} + \textit{total relative density of sp.x}) \,/\, 3 \tag{1}$$

2.3. Grazing observations

Cattle were observed in two herds (A and B) of two different farmers (F3 and F4), one in each division, in a two-week time frame in late October and early November 2019. In 12 days of observations, a total of 10 different animals were observed, 5 from herd A and 5 from herd B, by 3 different observers. Observations took place in the first three hours of grazing. In a five-minute interval, the observer noted the predominantly consumed species and the respective stratum for their animal. Five strata were distinguished, IR, HP, TTD, the side of a paved road (RS), and when feeding on epiphytic plants growing on the tree trunk (TT) itself. If due to the terrain and distance of the observer to the animal, it was not possible to determine the exact species consumed in one observation interval of 5 minutes, but the animals were observed consuming grass, the dominant species was noted as “grass mixture”.

2.4. Sample diet composition and nutritional quality

A sample diet was constructed for the cattle in this study, to outline the average nutritional quality of biomass consumed by animals from grazing the plantation undergrowth. The sample diet was made up of eight species that were identified as the major forage plants, based on the frequency of their occurrence during animal observations. The contribution of each identified plant species to the composition of 1 kg DM of the sample diet (g kg^{-1} DM) was calculated as displayed in Eq. 2. Hereby, the species-specific contribution is based on the observation count for the respective species relative to the summed total observation count of all species in the sample diet.

$$\text{proportional contribution species DM}_i = \textit{species count}_i \Big/ \sum_{i=1}^{8} \textit{species count}_i \times 1000\text{g} \tag{2}$$

Subsequently, the count for “grass mixture” was reallocated proportionally among the four identified grass species. For this, the counts of the four predominantly observed grass species *Axonopus compressus* (Poaceae), *Ottochloa nodosa* (Poaceae), *Cyrtococcum oxyphyllum* (Poaceae), and *Arthraxon hispidus* (Poaceae) were summed, and the contribution of each species was calculated as the ratio of species count to total grass count, excluding “grass mixture” and all non-grass counts. Then, the count of “grass mixture” was distributed among the four grass species according to their proportion. The adjusted count for the grass species was used to calculate the composition of 1 kg of the sample diet based on the contribution of each species to the adjusted total count of plant species in the sample diet. Other species and activities identified during intake observations were excluded from this calculation. Furthermore, it was assumed that the intake rate, meaning the DM ingested per unit of time, is the same for all species in the sample diet.

Subsequently, samples of the species composing the sample diet were taken from all quarters of both divisions of the plantation for laboratory analysis. Grasses were harvested at a height of 2.5 cm above ground, including individuals with and without inflorescence and of different heights. Ferns were sampled at various stages of maturity, including the rachis but excluding rhizomes. The legume plant *Pueraria phaseoloides* (Fabacea) was sampled including stalks, whereas large rhizomes were not sampled. Collection of hanging and stacked palm fronds was done by mimicking cattle feeding behavior by cutting off the leaflets and discarding the rachis.

Differences in composition and nutritional quality of individual species were assumed to be negligible within a division, and therefore samples of the same species were pooled to yield one sample per division. Samples were dried first by sunlight for 48 h, then in an oven at 55°C for 48 h. In total, 16 samples (8 species by two divisions) with a minimum of 100 g DM were taken to the Eurofins Agro laboratory in Wageningen, the Netherlands. The laboratory assessed the crude protein (CP) content using the Kjeldahl (1883) method, the crude ash (CA) content (laboratory own method), and the in-vitro digestible organic matter (DOM) using the Tilley & Terry (1963) method.

Finally, DOM in %, the CP and CA content both in g kg^{-1} of 1 kg DM of the sample diet were calculated from the results of the analysis of the individual species. Further, the metabolizable energy content of the diet (ME_{diet}, MJ kg^{-1} DM) was calculated from DOM according to Eq. 3 (Freer et al., 2007).

$$ME_{diet} = 0.169 \times DOM - 1.986 \tag{3}$$

2.5. Live weight calculation

The hip height (HH) was measured on 25 animals age ≥ 1 year from the herds A and B, using a tape measure set from the animal’s hip bones (hooks) to the ground when standing on a level surface. LW was calculated from HH according to Franco et al. (2017). The formula, as presented in Eq. 4, displays the quadratic relationship between LW and HH ($r^2 = 0.84$) and is derived from data of Holstein-Zebu crosses in Brazil.

$$LW\ (kg) = 2570.22 - 45.8572 \times HH + 0.2203 \times HH^2 \quad (4)$$

The respective tropical livestock unit coefficients (TLUc) were calculated from the FAO guideline, where one livestock unit equals 500 kg LW (Upton, 2011). TLUc for buffalos were calculated based on LW values reported by Presicce (2017). The TLUc for Kedah Kelantan cattle were adjusted according to the calculated average cattle LW. Hereby, separate coefficients were calculated for mature female, mature male, immature female, and immature male individuals of both species (Wibawa et al., 2009; Appendix 5). In the calculation of stocking density, maturity and sex were considered by multiplying the respective number of animals of a particular sex and maturity with the corresponding TLUc. The total TLU of immature animals per division was calculated according to the general assumption that 50 % of the immature animals are male and 50 % are female, as well as that 25 % of immature female and male animals had an LW of 25 % of the respective adult LW, 50 % had an LW of 50 % of the respective adult LW and 25 % had an LW of 70 % of the respective adult LW.

2.6. Stocking density calculation

Information gathered during interviews on the number, sex, and age of animals kept in the plantation was used for the calculation of the stocking density in tropical livestock units per hectare (TLU ha^{-1}) for each division as displayed in Eq. 5 Where *i* is the group of animals with a particular sex and maturity, TLU is tropical livestock unit and *c* is the TLU coefficient.

$$stocking\ density\ (TLU/ha) = \sum_{i=1}^{16} number\ animals_i \times TLUc_i / total\ division\ ha \quad (5)$$

The calculated stocking density (Eq. 5) was then compared to the carrying capacity of natural undergrowth under oil palm plantations in Malaysia of 0.11 TLU ha^{-1} as estimated by Dahlan & Wahab (2014). The stocking density includes buffalo grazing inside the plantation. Our carrying capacity was based on feed availability per division and areas that typically do not grow forage (TTD) were not subtracted from this calculation. As every plantation is expected to have such exclusion zones, the calculation is still representative, and results are comparable to other plantations.

2.7. Animal nutritional requirements

Metabolizable energy (ME) and CP requirements for maintenance (CP_m and ME_m) as well as the minimum daily Dry Matter Intake (DMI) to cover ME_m (DMI_m) in kg d^{-1} were calculated according to Freer et al. (2007)(,Appendix 4). Further, it was assumed that covering approximately 250 % of the animal's ME_m is sufficient to cover ME requirements for maintenance, growth, gestation, and lactation (ME_{req}; Moran, 2005; Sales et al., 2015). The same assumption was made for CP requirements for maintenance, growth, and reproduction (CP_{req}). Additionally, the maximum DMI capacity (DMI_{max}) in kg d^{-1} was calculated as 2.5 % of LW, a simplified calculation approach adopted from Freer et al. (2007). The maximum ME intake capacity (ME_{max}) and the maximum CP intake capacity (CP_{max}) were then calculated based on DMI_{max} multiplied with the sample diet CP content (CP_{diet}) and ME_{diet}, respectively.

Based on the DMI_{max}, the annual feed intake per animal was calculated in kg DM y^{-1} ($feed_{int}$) as displayed in Eq. 6.a, for mature and immature female and male cattle. For this, the DMI_{max} for immature cattle was assumed to be 50 % of the respective mature DMI_{max}. The average feed intake in kg DM ha^{-1} y^{-1} ($feed_{intha}$) was calculated for D1 and D2 as displayed in Eq. 6.b. The calculation of feed intake requirements includes cattle only and excludes buffalos.

$$feed_{int}\ (kg\ DM / y * animal) = \sum_{categories} DMI_{max,\ category} \times 365 \quad (6.a)$$

$$feed_{intha}\ (kg\ DM / ha \times y) = feed_{int} \times number\ of\ animals_{division} / ha_{division} \quad (6.b)$$

Additionally, the suitability of the sample diet to meet animal requirements was assessed, by calculating the number of times ME (ME_x) and CP (CP_x) requirements for maintenance were met at maximum DMI capacity, as displayed in Eq. 7.a and 7.b.

$$ME_x\ (MJ\ ME / d) = ME_{max} / ME_m \quad (7.a)$$

$$CP_x\ (g\ CP / d) = CP_{max} / CP_m \quad (7.b)$$

3. Results

3.1. Undergrowth composition

In 72 sampled quadrats 18 species were identified with relevant quantities (Appendix 6) and a total of 733.1 g DM was collected. The most frequent species are the grasses *A. compressus, O. nodosa, C. oxyphyllum, A. hispidus,* and the fern *Adiantum latifolium* (Pteridaceae), occurring in 72 %, 71 %, 51 %, 28 %, and 21 % of the sampled quadrats, respectively. Correspondingly, the total collected biomass was highest for *O. nodosa, A. compressus, C. oxyphyllum, A. hispidus*, and *A. latifolium*, with 362.4 g DM, 149.6 g DM, 80.7 g DM, 57.4 g DM, and 34.9 g DM from all quadrats combined, respectively. *O. nodosa* showed the highest total relative dominance, accounting for 49 % of all collected biomass in g DM, and consequently showed the highest SDR, of 59 %. The second and third most dominant species according to their SDR were the grass species *A. compressus, C. oxyphyllum*, followed by the fern *A. latifolium.* The five species with the highest frequency also showed the highest SDR and made up 90 % of all counted individuals and 92 % of all collected biomass in g DM. Sward height was significantly lower in D1 ($P < 0.001$), with an average of 7.8 cm compared to 12.7 cm in D2 (Appendix 7). Ground cover was significantly higher in the HP compared to the IR ($P = 0.01$) and was significantly higher in the northwest compared to the southwest quarter in D1 and significantly higher in the central compared to the southwest quarter in D2 (Appendix 7).

3.2. Grazing observations

During visual observations in the first 3 hours of grazing, 16 different consumed plant species and cattle activities were noted (Appendix 9). Animals grazed 914 out of 950 observations, which equals 96 % of the time. Animals spent only 4 % of the observation time ruminating, resting, feeding on fresh palm fruits, and drinking water or milk. Along with grasses, cattle were observed to favor the frond of the oil palm *Elaeis guineensis* (Arecaceae) as well as the epiphyte *Davallia denticulata* (Davalliaceae). The leguminous cover crop *P. phaseoloides* only occurred in limited locations throughout both plantation divisions, as it is intentionally planted for improvement of N-availability and prevention of soil erosion at tree establishment and tends to disappear when trees grow older and shading increases (Samedani et al., 2014). Where

Table 2
Plant species composing the sample diet for cattle grazing the oil palm plantation; the corrected total count of each species based on intake observations and the proportion of each species to the total counted positions (n = 897) in g per kg dry matter intake (DMI).

Species	Count	Proportion g/kg DM
Axonopus compressus	571	637
Elaeis guineensis	160	179
Ottochloa nodosa	46	51
Cyrtococcum oxyphyllum	40	45
Adiantum latifolium	25	28
Arthraxon hispidus	23	26
Pueraria phaseoloides	16	18
Davallia denticulata	15	17

present, it was favored by the cattle.

With a total of 563 counts, the most frequently consumed species in both divisions was “grass mixture”, accounting for 70 % and 40 % of total consumed biomass in D1 and D2, respectively. Following the reallocation to the respective species (*A. compressus, O. nodosa, C. oxyphyllum*, and *A. hispidus)*, the two most frequently consumed species were *A. compressus* with a frequency of 63 % and *E. guineensis* with 18 % (Table 2, Appendix 10). Both species were consumed more freuqently in D2 compared to D1 (Appendix 11). The third most frequently consumed species was *O. nodosa* with 5 %, followed by *C. oxyphyllum* with 4 %. The species consumed differed between divisions, e.g. cattle in D1 were not observed consuming *P. phaseoloides*, whereas in D2 the species amounted to 6 % of total observations.

Animals were observed feeding on a greater variation of plant species than is captured by the observation protocols and displayed in Table 2. Among others, animals were occasionally observed feeding on broad leaf species such as *Ageratum coryzoides* and *Asystasia intrusa*, grasses such as *Paspalum conjugatum* and *Paspalum commersonii* and the legume *Mimosa pudica*. However, these species occurred less frequently and were consumed only in low quantity compared to the species listed in Table 2. Therefore, they did not appear in the systematic observations.

3.3. Sample diet composition and nutritional value

The plantation undergrowth was considered the only feed source, as additional dry matter intake from alternative areas was negligible and no additional feed was given on a regular basis. The sample diet is composed of the eight dominantly consumed plant species, based on intake observations. The proportional contribution of each species to the sample diet in g per kg DM is displayed in Table 2, together with the observed intake count. The four grass species *A. compressus, A. hispidus, C. oxyphyllum*, and *O. nodosa* made up 76 % of the sample diet, with *A. compressus,* being the largest component, contributing 64 % of the cattle diet. The second largest component was the fronds of *E. guineensis* with 18 %. The final 6 % of the diet was composed of the fern *A. latifolium*, the legume *P. phaseoloides* and the epiphyte *D. denticulata*.

Differences in digestible organic matter (% DOM), metabolizable energy (MJ ME kg^{-1} DM), crude ash (g CA kg^{-1} DM) and crude protein (g CP kg^{-1} DM) were not significant between plantation divisions (Appendix 12). The CA, CP, DOM, and ME content of the plant species in the sample diet are displayed in Table 3. The sample diet contained 151 g CP kg^{-1} DM and 95 g CA kg^{-1} DM. The DOM content was 52 %, and the ME content was 7.5 MJ ME kg^{-1} DM (Appendix 13).

3.4. Animal live weight and stocking density

The average hip height (HH) for all measured animals (n = 25) was 121 ± 6 cm. The overall average LW was 252 kg ± 43 kg. The average LW of female cattle (n = 21) was 250 ± 32 kg and the average LW of male cattle (n = 4) was 265 ± 86 kg. The stocking density of 0.30 TLU ha^{-1} in D1 equals 151 kg LW ha^{-1} and the stocking density of 0.10 TLU ha^{-1} in D2 equals 51 kg LW ha^{-1} (Appendix 5, Appendix 8). In D1, the stocking density was higher than the maximum of 0.11 TLU ha^{-1} recommended by Dahlan & Wahab (2014). In D2, the stocking density was just below the recommendation.

Table 3
Digestible organic matter proportion (DOM %), crude ash (CA) and crude protein (CP) contents in g/kg DM and metabolizable energy (ME) content in MJ/kg DM as the average for the two divisions of the oil palm plantation of eight plant species composing the sample diet of cattle grazing the oil palm plantation.

Species	CA	CP	DOM %	ME
Adiantum latifolium	90	170	28.1	2.9
Arthraxon hispidus	158	161	72.4	11.5
Axonopus compressus	99	156	57.5	8.5
Cyrtococcum oxyphyllum	123	167	49.8	7.1
Davallia denticulata	75	123	59.7	9.0
Elaeis guineensis	66	123	31.7	3.6
Ottochloa nodosa	112	128	55.2	8.1
Pueraria phaseoloides	42	279	48.0	6.7

3.5. Cattle requirements and feed supply

The average per head maintenance requirement for ME_m and CP_m in adult cattle (n = 25, average LW = 252 kg ± 43 kg) were 30 ± 5 MJ ME d^{-1} and 114 ± 13 g CP d^{-1}, respectively. The corresponding average per head DMI_m was 4.0 ± 0.7 kg DM d^{-1}, while the average per head total requirement for ME_{req} and CP_{req} was 75 ± 13 MJ ME d^{-1} and 286 ± 33 g CP d^{-1}, respectively. The average per head DMI_{max}, the corresponding ME_{max} and CP_{max}, as well as the resulting ME_x and CP_x (according to eq. 7.a and 7.b) are displayed in Table 4. The average CP_x of 8.36 ± 0.74 was higher than the 2.5 times CP_m, or 250 % CP_m, suggesting a surplus in protein supply at DMI_{max}.

The average ME_x of 1.60 ± 0.16 indicates that energy requirements for maintenance are covered at a maximum feed intake capacity to 160 % (Table 4). Thus, the sample diet covered only 64 % ± 7 % of the estimated total requirements of 250 % ME_m. Hence, energy seems to be more limiting for growth and production than protein.

The average per head for $feed_{int}$ was 2,330 ± 389 kg DM y^{-1} (n = 25). The female average for $feed_{int}$ was 2,227 ± 209 kg DM y^{-1} (n = 21), and the male average $feed_{int}$ was 2,874 ± 671 kg DM y^{-1} (n = 4). Based on the number of cattle currently grazing in the plantation and the available grazing area, this results in a total $feed_{intha}$ (eq. 6.a and 6.b) of 858 kg DM ha^{-1} y^{-1} in D1 and 443 kg DM ha^{-1} y^{-1} in D2.

4. Discussion

4.1. Undergrowth composition

As a result of the strategic positioning of the quadrats and subdivision of the sampling area, it was possible to obtain a representative sample as fit the requirements of this study. The quadrat sampling method does not depict all species available as feed to the livestock, such as epiphytes and hanging or stacked palm fronds. These missing species were counted in the intake observations and sampled separately for analysis, to include their contribution to the diet (Table 3). Intake observations show that the majority of intake is from the ground growing plants and these species are adequately depicted by the quadrat method (Table 2, Appendix 10). Furthermore, the plant species consumed by grazing cattle (Appendix 9), can be assumed to strongly correlate with the sampled plant species (Appendix 4), as quadrats were positioned in recently grazed areas. Species identification can lead to some errors. However, we triangulated between information in the field guide, smartphone application and online searches. Further, similar botanical composition of the undergrowth was found by Dahlan et al. (1993) and

Table 4
Average maximum dry matter intake capacity (DMI_{max}) in kg d^{-1}, metabolizable energy intake capacity (ME_{max}) in MJ ME d^{-1} and crude protein intake capacity (CP_{max}) in g d^{-1} as well as the coverage of maintenance requirements at maximum intake capacity for ME (ME_x) and CP (CP_x) of female and male Kedah Kelantan cattle grazing in oil palm plantation undergrowth.

	DMI_{max}	ME_{max}	ME_x	CP_{max}	CP_x
Average*	6.4	47.6	1.60	961	8.36
SD	1.1	8.2	0.16	166	0.74
female av.**	6.3	47.3	1.65	954	8.51
female SD	0.9	6.5	0.11	130	0.59
male av.***	6.6	49.5	1.32	999	7.60
male SD	2.1	16.1	0.13	324	1.05

* n = 24, LW average = 252kg;
** n = 21, LW average = 250kg;
*** n = 4, LW average = 265kg

Samedani et al. (2014) in Malaysian oil palm plantations. Luke et al. (2019) reported similar plant species but a lower concentration of grass species such as *C. oxyphyllum* and *A. compressus* in the IR and HP from palm oil plantations in Indonesia. Therefore, we estimate that errors in species identification were minor.

The significantly higher sward height in D2 compared to D1 could be explained by a lower intensity in grazing and mechanical maintenance in D2, resulting from the lower stocking density and the difference in terrain structure, as well as the distance of D2 to the plantation headquarters. The terrain structure in D2 along with the younger palm trees with lower hanging fronds complicate vehicular access to certain harvesting paths, reducing the diligence and frequency of maintenance activities. Further, the higher ground coverage in the HP compared to the IR, and in frequently grazed areas such as the SW quarter of D1 and the SW and SE quarters of D2 is in line with findings of Tohiran et al., 2019a) that frequent grazing improved ground coverage, as opposed to herbicide application, which often results in complete exposure of topsoil. Similarly, Luke et al. (2019) found a significant reduction in biomass and vegetation cover at elevated herbicide application compared to regular vegetation management. Thus, increasing the stocking density in D2 may improve biological weed control throughout the division and help in controlling sward heights, while simultaneously improving lateral growth and ground coverage to improve soil quality and path firmness and to prevent soil compaction and erosion (McDonald, 2005; Popp et al., 1997).

4.2. Grazing behavior and sample diet composition

The nutrient contents calculated for the sample diet from the analyzed nutrient contents of the individual species (Table 3) can be assumed to be highly representative of the actual diet from the plantation undergrowth. Based on visual intake observations, the species included in the sample diet make up the majority of the cattle diet. Animals were observed consuming a few species not included in the sample diet, but this comprised only a fraction of the intake. More detailed grazing observations in future studies, for example via shorter observation intervals, could lead to an even more precise depiction of the species intake, as well as the inclusion of more species in the sample diet.

The sample diet energy content of 7.5 MJ ME kg DM^{-1} (Appendix 13) exceeds the reported 4.6 – 7.0 MJ ME kg DM^{-1} in plantation undergrowth by Dahlan et al. (1993). However, Dahlan et al. (1993) did not consider selection by cattle, but analyzed the entire standing biomass. Discrepancies in the SDR of plant species and the intake frequency observed – such as the preference of *A. compressus* over the more common *O. nodosa* (Table 2, Appendix 10) suggest a selection process, highlighting an active effort by the animals to feed on specific plants, despite lower availability. Therefore, it can be assumed that the oil palm undergrowth allows grazing cattle to select preferred, highly palatable species when available, spurning less preferred species. This is further underlined in the active selection of *E. guineensis* fronds, *D. denticulata* from the TT, and *P. phaseoloides* in D2, as well as the discrepancy between SDR and intake observations of *A. compressus* and *O. nodosa*. Conversely, relatively low intake of high-energy species such as *A. hispidus* and *D. denticulata* may be attributed to the species' low SDR. With energy being the limiting factor for growth and production, animals are likely to select species high in energy.

E. guineensis recorded in undergrowth sampling refers solely to shoots, which occur only irregularly in patches where harvested fruit bunches were left on the ground and scattered fruits sprouted, resulting in a low SDR. The growth of oil palm shoots is not desired by plantation management. Therefore, controlling shoot growth via livestock grazing could benefit plantation management by reducing weeding efforts and costs (Gabdo & Abdlatif, 2013; Latif & Mamat, 2002).

In turn, the majority of *E. guineensis* consumed during grazing observations (Table 2) refers to hanging or stacked fronds, which are recurrent throughout the plantation with higher frequency and dominance than the palm shoots. In D2 the cattle were observed feeding on palm fronds more often than in D1. Tree age in the SW quarter of D1, where the observations took place, is higher than in D2 and hanging fronds were out of reach. While cattle feeding on hanging fronds is considered a threat to oil palm productivity, fronds are frequently removed from palm trees during the harvesting process and regular pruning rounds and are therefore abundant throughout the plantation (Gabdo & Abdlatif, 2013). Loh (2017) estimated a production of pruned oil palm fronds of 10.4 t ha^{-1} – roughly 50 % of total accruing fronds – that can't be transported from the plantation and are considered waste, as they are not suitable for selling as feedstuffs to intensive livestock systems.

Furthermore, exporting fronds would export nutrients that subsequently need to be replenished. While oil palm fronds have been identified as suitable cattle feed (Ishida & Abu Hassan, 1997), recycling fronds directly within the plantation (Woittiez et al., 2017) or as feed for cattle grazing in the plantation can both help in stabilizing nutrient flows.

Stacking of pruned fronds in the inter-row is a common practice to thwart soil degradation following erosion, a major concern in palm oil plantations (Afandi et al., 2017). Therefore, cattle feeding on stacked fronds raises concerns about interference with the mulching function of pruned fronds. Another viable strategy to counteract soil erosion in plantations is planting cover crops, such as *P. phaseoloides*, as vegetation cover can prevent soil runoff (Afandi et al., 2017; McDonald, 2005). While studies have shown that trampling by livestock can negatively impact vegetation cover and promote soil compaction (Greene et al., 1994), new studies underline the potential of targeted grazing to improve desired vegetation cover, thus reducing the risk of soil erosion (Frost et al., 2012; Hendrickson & Olson, 2006; Tohiran et al., 2019a). High frequency, low-intensity rotational grazing management has been shown to simultaneously increase vegetation growth and animal productivity (Savian et al., 2021; Schons et al., 2021) as the nutritional quality of regrowth is high, and low grazing intensity allows for selective grazing. Thereby, rotational livestock grazing can target to alter the undergrowth vegetation via grazing at specific time periods, when undesired species are vulnerable to defoliation (Frost et al., 2012; Popp et al., 1997). Moreover, a reduction in herbicide use following weed containment via grazing can help restore habitats and improve the biodiversity of insects and animals in plantations, thus recovering important ecosystem services (Tohiran et al., 2017, 2019a,b).

4.3. Cattle live weight

The large SD in HH for males (83 kg LW) derives from the small number of individuals and the extensive age difference. Based on visual observations of the body condition and size of the measured animals, lower LW values would have been expected than the 265 kg for males and 250 kg for females, when comparing to literature reported LW of purebred Kedah Kelantan. Mohd Hafiz et al. (2019), reported for instance weight averages of 214.5 kg of male and 173.7 kg for female Kedah Kelantan cattle which are 20-30 % lower than the values in this study. This suggests that the formula used for LW calculation leads to an overestimation of the LW. Possibly, because the formula by Franco et al. (2017) is based on Holstein-Zebu crosses, which are on average larger and heavier than the Kedah Kelantan and will thus have a different bone structure and presumably a higher relative body weight. Further, 88 % of the cattle grazing the plantation is presumably smaller than the average measured HH and, thus, lighter than the average calculated LW, as the larger herds of F2 and F5 were predominantly purebred Kedah Kelantan, whereas the observed herds of F3 and F4 comprised higher percentages of larger crossbreds. Similarly, Dahlan & Wahab (2014) assumed higher LW for crossbred cattle in their calculations. Because of the potential overestimation of cattle live weight, the actual stocking density in terms of TLU and the calculated maintenance needs and feed requirements of the cattle may also have been overestimated. This means that the vegetation might cover a higher percentage of the total energy requirement of 250 % ME_m.

4.4. Cattle requirements and feed supply

The DMI_{max} limits the possible daily nutrient intake. Results of animal requirement calculations and the sample diet nutritional quality indicate that the undergrowth quality is adequate to supply livestock with 335 % of the required protein at DMI_{max} (Table 4). Energy supply may however be limiting growth and production during some phases, as DMI_{max} covers only 160 % of ME_m, which is 60 % of ME_{req} (Table 4). Especially when energy requirements are high, the sample diet may provide insufficient energy, for example in young animals growing rapidly and in some phases of gestation and lactation. Similarly, ME requirements of adult male cattle are likely to be lower than those of adult female cattle, as no energy is required for gestation and lactation. However, ME_x is lower for males compared to females (Table 4) due to the calculation approach based on a multiple of LW. Given that LW might have been overestimated as a result of the calculation approach, the ME_m and CP_m (and subsequently ME_{req} and CP_{req}) might also have been overestimated. Further, not all animals require 250 % of ME_m at all times. As gestating and lactating animals are unlikely to be growing and vice versa, increase in requirements will be temporally shifted (Linn, 2003). Therefore, the average ME_{req} may be overestimating the actual total energy requirements and the potential energy supply of 160 % of ME_m (Table 3) may be closer to covering total requirements.

It follows, that possibly the sample diet is better able to supply the required nutrients than results suggest and may allow for a slightly higher production per animal. This is supported by farmers' statements that the undergrowth supplies sufficient nutrients. Nevertheless, additional nutrient supply, especially for lactating and gestating cows in situations of high energy demand, could be enhanced through the use of by-products from palm oil production such as palm kernel cake. A closer collaboration of the livestock farmers with the plantation on this matter could facilitate the supply of by-products from palm oil production to livestock farmers but requires the company's increased interest in the integration. It may also lead to additional costs for livestock farmers. Nevertheless, as prior research shows, systematic management and cooperation of involved parties increase the probability of mutual benefits and success of the system (Awaludin, 1999; Ayob, 2009; Latif & Mamat, 2002). Exchanging manure accumulating in the night quarters for oil palm by-products could be a solution with mutual benefits. Possible deficiencies in energy supply could be mitigated, while simultaneously increasing soil nutrient supply with organic fertilizer. Recycling cattle manure would help to retain nutrients and close nutrient cycles of the plantation.

Based on estimated DM yield of 500 kg ha^{-1} y^{-1} in mature oil palm plantations as reported by Latif & Mamat (2002), the estimated $feed_{intha}$ potentially exceeded the available DM in D1, whereas $feed_{intha}$ was slightly lower than 500 kg ha^{-1} y^{-1} in D2. However, the DM yield for plantation undergrowth under 5-year-old palm trees of 1,788 kg ha^{-1} y^{-1} reported by Haji Baba et al. (1998) for Malaysian plantations indicates that feed requirements can be met by the plantation undergrowth in the study area and that there is room for farmers to increase the stocking density. Changes in the estimated total ME requirements as well as any deviation from the estimated maximum intake capacity, will result in a proportional change in feed intake and, thereby, will affect the possible stocking density estimate.

Nevertheless, it should be considered that pruned palm fronds contribute to feed availability to a great extent and are not considered in the feed availability calculation in this study or the studies by Haji Baba et al. (1998) and Latif & Mamat (2002). Further, feed requirements may also be overestimated because of the LW overestimation. However, the 60 buffalos grazing in the plantation were not included in the feed requirement calculations.

The stocking density of 0.10 TLU ha^{-1} calculated for D2 is below the recommended value, suggesting that slightly more animals could be held in D2 and that feed supply is sufficient. Conversely, the calculated stocking density of 0.30 TLU ha^{-1} for D1 is above the estimated carrying capacity of 0.11 TLU ha^{-1} (Dahlan & Wahab, 2014). Buffalos were included in the stocking density calculation. Despite a possible small overestimation of LW and hence TLU of the current herd, this suggests that animal numbers should be reduced to avoid overgrazing. However, if systematic rotational grazing management is applied, potential increase in vegetation growth may allow for a higher carrying capacity than described by Dahlan & Wahab (2014) (Savian et al., 2021; Schons et al., 2021) Additionally, (Tohiran et al., 2019b), found that the carrying capacity of the oil palm plantation was highest in Negeri Sembilan, compared to two other Malaysian states, suggesting that a carrying capacity exceeding the estimated average can be expected.

Observations of the available undergrowth biomass in both divisions indicate an abundance of available feed, suggesting that the estimated carrying capacity reported by Dahlan & Wahab (2014) underestimates the actual carrying capacity. This is further underlined by the fact, that mechanical weeding processes continue despite grazing animals. Additionally, animals showed a tendency to conveniently graze the same areas surrounding the respective farmers' home base, while more remote areas were less frequented. Establishing more systematic grazing management could help in redirecting livestock to less frequently grazed areas and, thereby, averting overgrazing and improving resource use (Frost et al., 2012). Thus, future research should focus on the extent the stocking densities could be increased when less frequented areas are visited more. As land scarcity and high feed prices are two major factors limiting beef production (Latif & Mamat, 2002; Nor & Rosali, 2014), sustainably increasing stocking densities in plantations could be a major strategy to increase beef self-sufficiency in Malaysia without creating the need to import livestock feed. Lower production costs for smallholders in integrated systems could free resources for veterinary care and special attention to reduce diseases and calf mortality. Further, improvements are required in herd management and marketing strategies, as well as the selection of local or crossbred livestock breeds that can withstand the climate conditions. However, based on observations in this case study, smallholders' knowledge and willingness to invest in these measures seem to lag behind.

The systematic use of animals for weeding can reduce labor and herbicide costs while reducing the negative environmental effects of chemical agents (Tohiran et al., 2017, 2019b). In the investigated system, however, livestock keeping is not officially recognized by the plantation and the established integrated system is based solely on an informal verbal agreement, violating the official plantation policy. Therefore, the effects of manure and the biological weeding by the livestock are disregarded in the strategic planning of plantation processes. However, previous studies have presented the importance of systematic management of grazing and livestock in integrated systems (Awaludin, 1999; Devendra, 2009; Latif & Mamat, 2002). Dahlan & Wahab (2014) underlined the importance of a cooperative business strategy to mitigate social challenges arising in integrated systems.

Positive effects of livestock-oil palm-integration on environmental protection and biodiversity, on productivity and associated land savings, as well as on resource use efficiency all fit with the objectives of global and national efforts to increase palm oil sustainability – such as the

Roundtable for Sustainable Palm Oil (RSPO), Malaysian Sustainable Palm Oil (MSPO), Indonesian Sustainable Palm Oil (ISPO) and the International Sustainability and Carbon Certification (ISCC).

5. Conclusions

In the studied oil palm plantation in the Malaysian peninsula, the nutritional quality of the undergrowth is sufficient to cover cattle requirements for protein. As it provides only approximately 1.6 times maintenance energy requirements, elevated energy requirements of lactating and gestating cows may not be fully met. Therefore, supplemental feeding of energy-dense by-products to lactating and gestating cows, such as palm kernel cake, may be a viable strategy to improve livestock productivity while simultaneously increasing resource use efficiency.

While the general benefit of strategic livestock grazing under oil palm due to increased resource use efficiency is clear, further research and economic analysis are required to give a definite recommendation for integration of cattle production by smallholders in oil palm plantations, as the plantation management and the smallholders may pursue different goals. Establishing a systematic rotational grazing strategy based on herding by smallholder livestock farmers, which prevents fencing costs, reduces weeding costs, and avoids expenses following damage of young palm trees, is required to increase the attractiveness of the integration for the oil palm plantation. Hereby, the use of livestock as biological weeding agents to reduce the use of potentially harmful herbicides should be viewed as a strategy for large-scale plantations to simultaneously improve sustainability and reduce production costs. The local availability of manure can provide additional environmental and economic benefits when it is used to replace or complement inorganic fertilizer.

As the undergrowth biomass availability and quality is sufficient for animal production, even without sowing of fodder species or optimal rotational grazing management, the integration of livestock production in oil palm plantations can allow for an expansion of beef production. It is, therefore, a viable strategy to help reach the goal of 50 % beef self-sufficiency, contributing to national food security in Malaysia. Integrating livestock in oil palm plantations is addressing prevalent environmental concerns. It not only reduces the need for herbicide and inorganic fertilizer use and potentially increases biodiversity within the plantation, but it also spares land compared to having the systems side by side, thus optimizing land use and thereby reducing the need for deforestation and associated biodiversity and carbon loss.

CRediT authorship contribution statement

Natascha A. Grinnell: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Aart van der Linden:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Badrul Azhar:** Resources, Writing – review & editing. **Frisco Nobilly:** Resources, Writing – review & editing. **Maja Slingerland:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

Conflict of interest: the authors declare no conflict of interest

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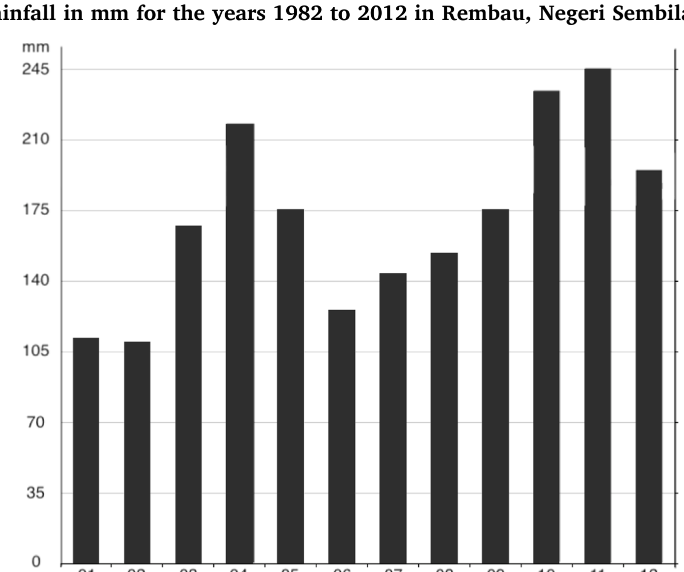
Appendix 1. Average monthly rainfall in mm for the years 1982 to 2012 in Rembau, Negeri Sembilan, Malaysia



Appendix 2. Soil quality parameters; Sand, silt and clay contents in mass fraction %, coarse fragments in volumetric %, soil organic carbon in t ha^{-1}, and soil pH (H_2O) for average soil in the study area near Pedas, Malaysia based on data from, https://soilgrids.org/#!/?layer=ORCDRC_M_sl2_250m&vector=1 (January 29th, 2020)

sand content soil depth	mass fraction in %	silt content soil depth	mass fraction in %
5 cm	40 - 60	5 cm	23 - 27
200 cm	35 - 45	200 cm	18 - 21
clay content		coarse fragments	
soil depth	mass fraction in %	soil depth	volumetric in %
5 cm	28 - 29	5 cm	2 - 15
200 cm	30 - 35	200 cm	9 - 15
soil organic carbon stock		soil pH (H_2O)	
soil depth	t/ha	soil depth	pH
5 - 15 cm	50	5 cm	4.2 - 5.1
0 - 5 cm	0 - 25	30 cm	4.8 - 5.2
60 - 100 cm	60 - 100	200 cm	4.9 - 5.4

Appendix 3. Total number of cattle and buffalos and the respective numbers of mature and immature female and male animals, the stocking density in division 1 and 2 expressed as tropical livestock units (TLU) and stocking density per hectare expressed in TLU ha^{-1}. 1 TLU = 500 kg live weight

	division 1	division 2
total number of cattle	189	20
breeding females	134	12
breeding bulls	4	1
immature cattle	51	7
total number of buffalos	60	0
breeding females	49	0
breeding bulls	4	0
immature buffalos	7	0
total cattle TLU	86	9
total buffalo TLU	46	0
TLU ha^{-1}	0.3	0.1

Appendix 4. Collection of equations used to calculate various positions throughout the study

$$\mathrm{ME_m}(\mathrm{MJ}/\mathrm{d}) = 1.2 \times \left(0.28 \times LW^{0.75} \times \exp(-0.03 \times A)\right)/k_m \tag{8.a}$$

$$\mathrm{k_m} = 0.02 \times ME_{diet} + 0.5 \tag{8.b}$$

$$\text{relative density of sp. x } (\%) = \textit{count of sp. x in quadrat y/total count of all sp. in quadrat y} \times 100 \tag{9}$$

$$\text{relative dominance of sp. x } (\%) = \textit{g DM of sp. x in quadrat y/g DM of all sp. in quadrat y} \times 100 \tag{10}$$

$$\text{frequency of sp. x } (\%) = \textit{number of quadrats containing sp. x/total number of quadrats} \times 100 \tag{11}$$

$$\text{total relative density of sp. x } (\%) = \textit{total count of sp. x in all quadrats/total counted individuals in all quadrats} \times 100 \tag{12.a}$$

$$\text{total reative. dominance of sp. x } (\%) = \textit{total g DM of sp. x in all quadrats/total g DM of all sp. in all quadrats} \times 100 \tag{12.b}$$

$$\text{endogenous urinary looses (EUP in g/d)} = 16.1 \times \ln(LW) - 42.2 \tag{13.a}$$

$$\text{endogenous fecal losses (EFP in g/d)} = 15.2 \times \text{kg } DMI_m/d \tag{13.b}$$

$$\text{dermal losses (DP in g/d)} = 0.11 \times kg\ LW^{0.75} \tag{13.c}$$

$$\mathrm{DMI_{max}}\ (\mathrm{kg}/\mathrm{d}) = 0.025 \times LW \tag{14}$$

$$\mathrm{DMI_{req}}\ (\mathrm{kg}/\mathrm{d}) = 2.5 \times ME_m/ME_{diet} \tag{15}$$

Appendix 5. Average live weight (LW) in kg for mature and immature cattle and buffalo (Presicce, 2017) of both sexes (female = f, male = m) and the respective tropical livestock unit coefficients (TLUc) for each group (i). Calculation basis is TLUc= 1 for animals of 500 kg LW. LW of immature cattle and buffalos was calculated based on the mature weights of the respective species and sex

mature cattle				mature buffalos			
i	sex	kg LW	TLUc	i	sex	kg LW	TLUc
1	m	311	0.62	9	m	500	1
2	f	259	0.52	10	f	400	0.8
calves in% of mature LW				calves in% of mature LW			
i	gender	kg LW	TLUc	i	gender	kg LW	TLUc
3	f 25%	65	0.13	11	f 25%	100	0.2
4	f 50%	130	0.26	12	f 50%	200	0.4
5	f 70%	181	0.36	13	f 70%	280	0.56
6	m 25%	78	0.16	14	m 25%	125	0.25
7	m 50%	156	0.31	15	m 50%	250	0.5
8	m 70%	218	0.44	16	m 70%	350	0.7

Appendix 6. The plant species identified during quadrat sampling, number of quadrats (n) in which the species occurred, total counted individuals, total biomass collected (in g DM) and the frequency of occurrence of a species relative to the total number of quadrats (n_{total} = 72). The average relative density (count of species relative to all counts of the quadrat) and dominance (species biomass relative to total quadrat biomass) of all plant species detected during quadrat sampling

Species					relative density		relative dominance	
	N	count	g DM	frequency in%	average	SD	average	SD
A. compressus	52	674	149.6	72.2	0.21	0.31	0.28	0.33
A. hispidus	20	624	57.4	27.8	0.39	0.36	0.39	0.4
A. latifolium	15	65	34.9	20.8	0.22	0.37	0.23	0.4
C. aciculatus	2	63	9.4	2.8	0.54	0.6	0.84	0.23
C. kyllingia	9	74	3.6	12.5	0.1	0.09	0.05	0.07
C. lappacea	9	52	8.5	12.5	0.06	0.07	0.08	0.12
C. oxyphyllum	37	811	80.7	51.4	0.29	0.29	0.27	0.34
C. prostrata	1	12	3.6	1.4	0.57		0.8	
C. sphacelatus	2	12	0	2.8	0.03	0.04	0	0
D. triflorum	5	191	25.2	6.9	0.35	0.31	0.25	0.34
E. guineensis	6	19	7.3	8.3	0.07	0.08	0.11	0.1
O. nodosa	51	3683	362.4	70.8	0.63	0.28	0.62	0.32
L. palmatum	4	9	0	5.6	0.03	0.02	0	0
M. diplotricha	4	23	0	5.6	0.04	0.04	0	0
M. pudica	2	2	0.6	2.8	0.01	0.01	0.04	0.06
P. pellucida	4	40	0	5.6	0.09	0.06	0	0
S. exilis	6	43	0	8.3	0.08	0.13	0	0
S. gracilis	1	4	0	1.4	0.06		0	0

Appendix 7. Weighted average (mean), standard deviation (SD) and number of observations (n) of the sward height in cm and the ground coverage with vegetation in % over all quadrats in every quarter, division and in total. NE = northeast, NW = northwest, SE = southeast, SW = southwest, C = central, N = north

division & quarter	sward height in cm		Ground cover in %		
	mean	SD	mean	SD	n
division 1	7.8	2.2	41.5	18.7	48
NE	7.5	2.2	48.4	23.0	12
NW*	7.9	2.9	36.4	13.1	12
SE*	7.2	1.8	32.9	17.1	12
SW*	8.5	2.0	48.5	16.8	12
division 2	12.7	4.2	44.5	19.5	24
C**	14.9	3.5	33.7	15.4	6
N	10.6	4.6	43.6	16.7	6
SE	12.7	4.1	48.5	20.9	6
SW**	12.5	4.2	52.4	23.7	6
Total	9.4	3.8	42.6	18.9	72

*significant difference (α=0.025) between SW and SE, SW and NW
** significant difference α=0.025between C and SW

Appendix 8. Animal data gathered during observations of two Kedah Kelantan herds from different Farmers (F3, F4), grazing inside the oil palm plantation. Number of animals (n), averages (av.) and standard deviations (SD) for body condition score (BCS), hip height (HH) and live weight (LW)

	overall	female	male
N	25	21	4
Av. BCS	2.1	2.1	2.5
SD BCS	0.5	0.5	0.4
av. age (y)	4.1	4.6	1.7
youngest (y)	1	2	1
oldest (y)	7	7	2
SD age	1.8	1.5	0.5
av. HH (cm)	121	121	120
SD HH	5.9	4.5	11.9
av. LW* (kg)	252	250	265
SD LW*	42.5	32.0	85.8
av. LW** (kg)	294	294	289
SD LW**	56.7	43.5	114.1

*Franco et al. (2017),
**Fordyce et al. (2013)

Appendix 9. Total count of activities and plant species intake observed during grazing observations in herd A (F3) and B (F4) with $n_{total} = 950$ observations

Species and behaviors	count
Grass mixture*	563
Elaeis guineensis	160
Axonopus compressus	99
Adiantum latifolium	25
Pueraria phaseoloides	16
Davallia denticulata	15
Desmodium triflorum	15
Resting	14
Ruminating	13
Ottochloa nodosa	8
Cyrtococcum oxyphyllum	7
Arthraxon hispidus	4
Drinking milk	4
Fresh palm fruits	4
Chrysopogon aciculatus	2
Drinking water	1

**A. compressus, O. nodosa, C. oxyphyllum, A. hispidus*

Appendix 10. Adjusted count of plant species intake observed during grazing intake observations and the proportion of each position relative to the total of n = 914 observations after proportional distribution of the position "grass mixture" among grass species

Species	adjusted count	frequency*
Axonopus compressus	571	62.5
Elaeis guineensis	160	17.5
Ottochloa nodosa	46	5.1
Cyrtococcum oxyphyllum	40	4.4
Adiantum latifolium	25	2.7
Arthraxon hispidus	23	2.5
Pueraria phaseoloides	16	1.8
Davallia denticulata	15	1.6
Desmodium triflorum	15	1.6
Chrysopogon aciculatus	2	0.2

*count relative to $n_{total} = 914$ observations

Appendix 11. Count of species intake observed during grazing observations in division 1 and division 2, along with the frequency as the ratio of species or activity count to total number of observations

Species	division 1 count	frequency*	division 2 count	frequency**
A. latifolium	6	0.01	19	0.07
A. hispidus	1	0.00	3	0.01
A. compressus	61	0.09	38	0.14
C. aciculatus	2	0.00	0	0.00
C. oxyphyllum	5	0.01	2	0.01
D. denticulata	9	0.01	6	0.02
D. triflorum	15	0.02	0	0.00
E. guineensis	91	0.14	69	0.26
grass mixture	456	0.70	107	0.40
O. nodosa	2	0.00	6	0.02
P. phaseoloides	0	0.00	16	0.06

*n_{total} = 648;
**n_{total} = 266

Appendix 12. Results of Student's t-test for significant differences for crude ash (CA), crude protein (CP), digestible organic matter proportion (DOM), and metabolizable energy (ME) between plantation division 1 and 2

	CA	CP	DOM	ME
SD	21.9	16.5	2.2	0.4
mean difference	-12.5	-14.6	1.5	0.3
std. error	7.74	5.85	0.79	0.15
P value	0.17	0.05	0.13	0.13

two tail probability, α=0.025

Appendix 13. The total CA, DOM, ME and CP content of the sample diet along with the contribution of each species to the total nutrient content of 1 kg dry matter of the sample diet

Species	CA g/kg	DOM %	MJ ME/kg	CP g/kg
Axonopus compressus	63.1	36.6	5.5	99.1
Elaeis guineensis	11.8	5.7	0.6	21.9
Ottochloa nodosa	5.8	2.8	0.4	6.6
Cyrtococcum oxyphyllum	5.5	2.2	0.3	7.5
Arthraxon hispidus	4.1	1.9	0.3	4.1
Adiantum latifolium	2.5	0.8	0.1	4.7
Pueraria phaseoloides	0.8	0.9	0.1	5.0
Davallia denticulata	1.3	1.0	0.2	2.1
Total	94.7	51.9	7.5	150.9

CA=crude ash, CP=crude protein, DOM=digestible organic matter, ME=metabolizable energy

Appendix 14. Average maintenance requirements in metabolizable energy (MEm), crude protein (CPm) and dry matter intake (DMIm) and the average requirements for maintenance, growth, gestation and lactation in metabolizable energy (MEreq), crude protein (CPreq) and dry matter intake (DMIreq) of Kedah Kelantan cattle grazing oil palm undergrowth

		ME_m	CP_m	DMI_m*	ME_{req}**	CP_{req}***
	n	MJ d^{-1}	g d^{-1}	kg d^{-1}	MJ d^{-1}	g d^{-1}
Average	25	29.9	114.4	4.0	74.6	286.0
SD	25	5.0	13.2	0.7	12.5	32.9
female av.	21	28.5	111.7	3.8	71.3	279.1
female SD	21	2.7	8.2	0.4	6.7	20.5
male av.	4	36.8	128.9	4.9	92.0	322.3
male SD	4	8.6	24.5	1.2	21.5	61.4

*DMI for ME_{diet} = 7.48 MJ ME kg^{-1} DM
**ME_{req} = 250% ME_m
***CP_{req} = 250% CP_m

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