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Monitoring herbage mass and pasture growth rate of large grazing areas: a comparison of the correspondence, cost and reliability of indirect methods

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Abstract

Timely grazing decision-making requires routine information on the herbage mass (HM) and pasture growth rate (GR). The aim of this study was to compare the correspondence, cost and reliability of two indirect methods –the comparative yield method (COMPYLD) and the pasture-meter (CDAX)– to estimate HM and weekly GR of a 42 ha grazing area. Weekly assessments from April 2017 to October 2018 were made with both methods to estimate HM and GR of 13 individual paddocks. In addition, estimated GR were compared to aerial net primary productivity (ANPP) estimated using remote sensing (SAT). Estimated HM was 22% lower for COMPYLD than CDAX ($HM_{COMPYLD} = 33 + 0.78*HM_{CDAX}$, $R^2 = 0.61$, CV = 17%, RMSE = 291 kgDM/ha). The correspondence between methods of estimated weekly GR of individual paddocks was weak ($GR_{CDAX} = 0.18*GR_{COMPYLD} + 19.1$, $R^2 = 0.05$, CV = 73%, RMSE = 21.8 kgDM/ha/d). However, when integrated in three-week moving-averages, over the complete grazing area, COMPYLD and CDAX yielded similar GR up to 35 kg DM/ha/d. Accumulating GR of the grazing area over one year resulted similar to annual SAT-estimated ANPP. These results imply that, on one hand, decisions based on nominal HM, such as target HM and grazing strip size, would need to be adjusted depending on the method, but on the other hand, decisions based in temporal trends or GR, such as size and timing of set-aside areas for reserves, would be unaffected by method. Compared with COMPYLD, CDAX would be advantageous whenever high labour costs offset higher amortization, maintenance and fuel costs, provided there is an alternative in place to monitor during downtime periods.

Introduction

Harvesting high amounts of forage by grazing demands timely grazing management decisions (Fariña *et al.,* 2011). This, in turn, requires frequent and consistent monitoring of herbage mass (HM) and growth rate (GR) in all of the paddocks that are part of a grazing area, i.e. area of the farm potentially grazable by the herd. The recent development of region-wide pasture monitoring databases, when associated with training on database management strategies (Turner *et al*., 2020), shows the value that frequent on-farm monitoring can have for pasture-based enterprises (Hanrahan *et al.,* 2017; Murphy *et al.,* 2018). The well-established close link between pasture monitoring and forage productivity, animal performance and profitability of pastoral dairy production systems (e.g. Sanderson *et al.,* 2001; Beukes *et al.,* 2019; Fariña and Chilibroste, 2019) has underlined the development of a multitude of on-farm pasture assessment methods aimed at short term grazing management (Thomson *et al*., 2001; Yule *et al.*, 2011; Insua *et al*., 2019; Legg and Bradley, 2020). However, it remains unclear how different methods compare in terms of standardization, ease to adopt, costs and reliability in relation to simpler visual approaches (O'Donovan *et al.,* 2002; Do Carmo *et al.,* 2020).

The most accurate method to measure HM is simply cutting, drying and weighing herbage, but estimating the average HM of grazed paddocks several hectares large and with substantial spatial heterogeneity demands a great amount of time to collect and process enough samples to ensure adequate representativeness (Catchpole and Wheeler, 1992). Therefore, there is a widely acknowledged need for cost-effective methodologies to estimate HM quickly and with reasonable accuracy for frequent monitoring of relatively large grazing areas in commercial farms. A lack of such tools is thought to be one of the reasons limiting the use of formal feed budgeting in farms (Clark *et al.,* 2006).

Many indirect methods exist for estimating the average HM of large areas. Visual assessment is the oldest, most simple and often the cheapest one. However, it requires training, and has potentially large operator bias (Catchpole and Wheeler 1992; 't Mannetje 2000; O'Donovan *et al.*, 2002). The comparative yield method (COMPYLD; Haydock and Shaw, 1975) captures spatial variation with a qualitative visual assessment of pasture mass (1 = low to 5 = high), and couples it with repeated calibration by cutting, weighting and drying samples. Although it has moderate accuracy, COMPYLD is quicker and has far lower costs than direct measurements ('t Mannetje 2000; O'Donovan *et al.*, 2002).

Herbage height, being more easily determined than mass, is used to infer HM by several indirect methods that differ primarily in how height is measured: with a ruler (Sanderson *et al.*, 2001), a sward stick (Barthram, 1986), a rising plate meter (Harmoney *et al.*, 1997; Lile *et al.*, 2001), and more recently with the rapid pasture meter C-DAX® (CDAX). The CDAX is an electronic device composed of an array of light emitting and sensing photodiodes capable of estimating herbage height at 200 Hz (CDAX; Agricultural Solutions, Ltd, Palmerston North, New Zealand; Yule *et al.*, 2011). The labour required by many height-based methods to monitor the grazing area of large farms remain substantial due to the high number of measurements required in heterogeneous pastures (Hutchinson *et al.*, 2016; Murphy *et al.*, 2018; Do Carmo *et al.*, 2020). Towed by a quad-bike, CDAX can cover more than 100 m^2/min, and has shown the potential to reduce measuring time by up to 85% compared to the rising plate meter (Schori, 2015). Its disadvantages include higher initial investment and potential downtime due to repairs. Considering that labour costs have become large on farms, savings in personnel-time could render CDAX, and other automated monitoring systems (e.g. Legg and Bradley, 2020), cheaper (Dennis *et al.*, 2015).

Remote sensing is another method able to capture vegetation spatial heterogeneity (Reinermann *et al.*, 2020). The Normalized Difference Vegetation Index (NDVI), and similar indices, integrate the low reflectance in the red wavelengths and high reflectance in the infrared typical of photosynthetic tissues. This makes possible to estimate aboveground net primary production (ANPP) using the NDVI to quantify the proportion of photosynthetically active radiation (PAR) absorbed by green vegetation (*f*PAR; Potter *et al.*, 1993; Oyarzabal *et al.*, 2011). Then, ANPP is estimated as the product of *f*PAR times incident PAR times an appropriate radiation use efficiency (RUE, Monteith 1972; Piñeiro *et al.*, 2006; Baeza *et al.*, 2011). This approach is hereafter referred to as SAT.

A great advantage of SAT is that the platform that carries the NDVI sensor provides near instantaneous large spatial coverage at minimal cost. Since mid-2017 complete grazing areas can be surveyed at a resolution of 10 × 10 m by Sentinel-2a products (sentinel-hub.com). Automated reports of satellite-based estimations of ANPP for forage resources are currently available in several countries as an input to support decision-making (e.g. lart.agro.uba.ar/observatorio-forrajero in Argentina, and https://ipasto.planagro.uy/public/seguimiento in Uruguay, based on MODIS imagery). Unfortunately, the implementation of MODIS-based ANPP estimation in dairy farms of Uruguay was unsuccessful because paddocks are typically smaller than the 250 × 250 m pixel size of MODIS (Chilibroste, 2009). But Sentinel-2 overcame this limitation. Three disadvantages of SAT are that (i) the frequency of available imagery can be low in cloudy areas, (ii) RUE and the relationship between NDVI and *f*PAR can depend on species, season and management (Piñeiro *et al.*, 2006), as well as on the imagery used (MODIS, SENTINEL, handheld sensor, UAV; Pellegrini *et al.*, 2020) and (iii) SAT cannot yet consistently and directly estimate HM (Reinermann *et al.*, 2020), although recent studies show promising results (Chen *et al.*, 2021; De Rosa *et al.*, 2021).

Grazing management decisions require information at several spatial scales. On one hand, HM of individual paddocks is useful to determine grazing cycles and length of time (e.g. paddock selection based on wedge plots), and spatially explicit paddock-level HM would further help determine more precisely daily strip-area to adjust forage allowance. On the other hand, trends in average HM and GR of the grazing area are needed to determine set-aside areas for reserves, or the need to supplement animals. Therefore, differences between monitoring methods can have distinct consequences depending on the scale and decision considered.

The aim of this study was to assess the correspondence and comparative costs and reliability of CDAX *v.* COMPYLD methods as tools to provide frequent and reliable monitoring of HM and GR of the grazing area of a dairy farm. Furthermore, we aimed at comparing GR derived from field measurements to ANPP estimated by SAT, under Uruguayan climatic and economic conditions.

Materials and methods

Experimental site

The study was carried out between April 2017 and October 2018 at an experimental dairy farm comprising 13 paddocks (2 to 4 ha each) located in the Centro Regional Sur of the Agronomy Faculty (Canelones, Uruguay, 34°36.810S, 56°13.088W). Average temperature was 19.6°C, with a lowest of 9.6°C in June and a highest of 30.1°C in January. A total of 2274 mm rainfall occurred during the 18-months experimental period with a monthly average of 105 ± 9.3 mm. Paddocks had either a mixture of lucerne *(Medicago sativa)* and bromus (*Bromus catharticus*) sown in March 2015 at 15 and 12 kg/ha respectively, or a mixture of dactylis *(Dactylis glomerata*) and white clover (*Trifolium repens*) sown in May 2016 and April 2017 at 20 and 3 kg/ha, respectively. All paddocks were fertilized with 40 kg P/ha/year as a single annual application, and with 200 kg N/ha/year, split in several applications throughout the year.

Determinations were made in the framework of a larger experiment where 96 Holstein–Jersey cross breed cows were allocated by parity (2.3 ± 1.3), body weight (BW) (534 ± 83 kg), body condition score (3.4 ± 0.45) to four treatments resulting from the factorial combination of two levels of stocking rate (1.5 or 2.0 milking cows per hectare) and two residual sward height (LR 4 cm residual sward height all year round and HR 6 cm sward residual height in autumn and winter, 9 cm in spring and 12 cm in summer). Thirteen paddocks were rotationally stocked and strip-grazed to control residual sward height, with a new strip subdivided by electrified fences provided after each milking. Grazing management was based on decision rules aimed at matching daily pasture consumption with the average GR of the grazing area (Holmes and Roche, 2007), while keeping average grazing area HM at 1800 kg DM/ha (measured through the COMPYLD method). Additionally, the phenological stage of grasses (number of leaves) and lucerne (number of internodes) was monitored weekly to ensure grazing intervals were adequate most of the time (i.e. two to three expanded leaves for grasses).

Estimation of herbage mass

For the COMPYLD method, HM was estimated every week along predefined transects in each paddock by taking 20 qualitative visual assessments per paddock (scale from 1 to 5, low to high HM). Every other week, in each paddock, the visual scale was calibrated against HM harvested at ground level, in quadrats (0.51 × 0.30 m), with hand scissors. Harvested fresh material was weighed and a 200–300 g aliquot dried for 48 h at 60°C to determine dry matter (DM) content. Throughout the study, a total of 193 linear regressions relating observed HM to the qualitative scale were fitted, with R^2 ranging between 0.40 and 0.80. A summary of accuracy and precision achieved in this repeated calibration is given in Supplementary Fig. S1. This procedure was carried out by the same two persons during the experiment.

For the CDAX method, the pasture meter CDAX® was driven weekly, by the same person, over the same predefined transect on each paddock, and HM was estimated using the equation calibrated by Waller (2020): HM (kg DM/ha) = 13.78 × $\text{height}_{\text{CDAX (mm)}}$ + 774, R^2 = 0.41. Cross-calibration results reported by Waller (2020) are summarized in Supplementary Fig. S2. This calibration included data collected between 2017 and 2018 in the same grazing area on which our study was carried out. Height was registered by the CDAX on sections of 6 m long and 0.3 m wide, and then all HM above 5 cm harvested with a lawn mower (Honda HRT 216) and weighed in fresh. A sample was taken and dried to estimate DM content. The residual HM left by the lawn mower was measured in by cutting to ground level with hand scissors three 0.51 × 0.30 m quadrats. Samples were weighed, dried and their DM content was determined. A total of 774 pairs of HM and CDAX height were included in the calibration, combining various pre- and post-grazing paddocks, as well as paddocks in intermediate stages of regrowth.

Estimation of weekly growth rate and accumulated pasture production

Paddock GR was estimated as the difference in HM between two consecutive measurements divided by the number of days between the two determinations (typically 7). Only paddocks which were not grazed in-between those two determinations were included in GR estimation. Moving averages of GR were estimated for time intervals ranging from 2 to 5-weeks. Weekly GR of the grazing area were accumulated over the complete 18 months experimental period to estimate cumulative pasture production.

GR estimation by satellite images (SAT)

Images provided by the Sentinel-2 platform (https://www.sentinel-hub.com/) were radiometrically corrected using a SCP complement available on QGIS (version 2.18.25, QGIS Development Team, 2019). Satellite imagery was available from July 2017 to June 2018 with a 5 day revisit time. Only images completely free of clouds were used. The GR of each paddock was estimated using the model by Monteith (1972):

$$\text{GR}_{\text{SAT}}(\text{kg DM/ha/d}) = \text{PAR} * \text{fPAR} * \text{RUE (g DM/MJ)} * 10 \quad (1)$$

where PAR is incident photosynthetically active radiation, f_{PAR} is the proportion of PAR absorbed by plants (unitless), RUE is the ratio of DM produced per unit of absorbed PAR (g DM/MJ PAR), and 10 is a factor to convert g DM/m^2 to kg DM/ha. RUE was assumed constant and equal to 0.9 g DM/MJ, a value locally established by Chilibroste (2009) from 169 biomass cuts made for annual and perennial forage species, between 2003 and 2005, and 2012 and 2013. Daily incident PAR was taken from the meteorological station at INIA Las Brujas, located 20 km away from the experimental site, and *f*PAR was estimated from NDVI as in Oyarzabal *et al.* (2011):

$$\text{fPAR} = \min[(1 + \text{NDVI})/(1 - \text{NDVI})/(11.62 - 1.55) \\ - 1.55/(11.62 - 1.55), 0.95)] \quad (2)$$

where NDVI is an index that integrates the reflectance in the infrared portion (IR, 0.75–1.00 µm) and the reflectance in the red portion of the electromagnetic spectrum (R, 0.60–0.70 µm), expressed as (IR-R)/(IR + R). Daily GR (kg DM/ha/d) was estimated using Eqn (1), interpolating *f*PAR linearly between dates without images (Oyarzabal *et al.*, 2011). Cumulative pasture production of the grazing area was estimated by accumulating daily GR of paddocks which were not under grazing at the date when the images were taken (so that it could be compared with those estimated by COMPYLD and CDAX).

Economic comparative evaluation

The cost of monitoring the grazing area using CDAX or COMPYLD was calculated considering (i) hours per year required to drive through the grazing area to collect and enter the information on HM and GR on a computer, (ii) the time required for training for each method, (iii) fuel and equipment maintenance and depreciation in case of CDAX. The investment for CDAX includes the acquisition of a quadbike which represents the 77% of the investment and the other 23% corresponds to the electronic device CDAX (US$ 15 200 and 4500 respectively). The lifespan of both tools was considered to be 1200 and 10 000 hours, and the residual value deemed to be 20 and 15% of purchasing price for the CDAX and quad-bike, respectively (Table 1). Amortization of the investment was calculated as:

$$\text{Amortization}_{\text{CDAX + quad-bike}} \\ \text{US /year} = \frac{\text{Investment US /year}}{\text{Lifespan hours/hours of use/year}} \quad (3)$$

Vehicle maintenance was estimated as the cost of three mechanical services per year, which includes fluid check (oil, filters, clutch and brakes). For COMPYLD, labour time was covered by hiring a person to perform the weekly walking through all paddocks of the grazing area to estimate HM, and the biweekly calibration in each paddock. Two weeks of training were budgeted to

Table 1. Amortization (US$/year) of the investment on a quad-bike and the pasture meter (CDAX) for perform herbage mass determinations (HM) on a complete grazing area of 42 ha with 13 paddocks

	Quad-bike	CDAX
Investment US$	15 200	4500
Lifespan quad-bike, hours	10 000	1200
Residual value	20%	15%
U$S/year	119	293

Lifespan and residual value are considering either for quad-bike and CDAX.

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adjust the methodology as detailed on the section *Estimation of herbage mass*. For CDAX, labour time was covered as part of the tasks of an operator of the farm. For the three methods, remuneration of labour was valued according to the average salary in Uruguayan dairy farms expressed in US dollars per hour which was estimated on US$/hour 9.29. The value of investment and labour cost were considered in accordance with Uruguay market value during 2017 and 2018 experimental period.

SAT implementation was considered free of cost, as a service that state agencies could provide, as indeed they do in Uruguay (e.g. https://ipasto.planagro.uy/public/seguimiento; http://www.eleche.com.uy/cooperarios/productores-seguimiento-forrajero-satelital?es), although a modicum of hours of training and information analysis regarding to download and process the satellite images was considered.

Statistical analyses

Linear regressions were fitted to compare HM and GR paddocks estimations (COMPYLD *v.* CDAX) using the REG Procedure of SAS. Additionally, the GLMMIX Procedure of SAS was used to compare HM and GR with method, month and pasture type and their interaction as fixed effects and paddock as a random effect. An autoregressive covariance structure was used in the model to account for repeated measures in time within paddocks. To compare differences on estimations of GR at the grazing area, mean values per month and method were calculated and a mixed model with method and month as fixed effect was used (GLMMIX Procedure of SAS). In all cases means were declared different when Tukey test resulted in $P < 0.05$.

Results

Herbage mass

The CDAX estimated consistently higher paddock HM than the COMPYLD method throughout the experimental period. The difference was larger at higher HM (Fig. 1). The relationship of HM estimated by the two methods fitted by linear regression was $HM_{COMPYLD} = 0.78\ (\pm 0.03)*HM_{CDAX} + 33.4\ (\pm 93.2)$ ($R^2 = 0.62$, $n = 231$, CV = 17%, RMSE = 291). Over the 18-months of study, estimated average HM of the grazing area varied between 1500 and 2766 kg DM/ha when estimated by CDAX, and between 1140 and 2200 kg DM/ha when estimated by COMPYLD (Fig. 2). Smallest differences between methods were observed in February 2017 (193 kg DM/ha), and largest in May 2017 (1138 kg DM/ha). The difference in HM estimated by CDAX and COMPYLD was evident in all pasture types, although seemed smaller in older pastures (Fig. 3: method*pasture type interaction; $P < 0.05$).

Growth rate

Weekly GR of individual paddocks was highly variable, ranging from 0 to 120 kg DM ha/d when estimated by either COMPYLD or CDAX (Fig. 4). The linear relationship between GR estimated by CDAX and COMPYLD, showed very low R^2 and high CV: $GR_{COMPYLD} = 0.18\ (\pm 0.07)\ GR_{CDAX} + 19.13\ (\pm\ 2.4)$ ($R^2 = 0.05$ $n = 231$, CV = 77%, RMSE = 21.8; Fig. 4). Although this relationship suggests that GR was higher for COMPYLD at lower values of GR, and higher for CDAX as values of GR increased, the high variability limits the certainty of this inference.

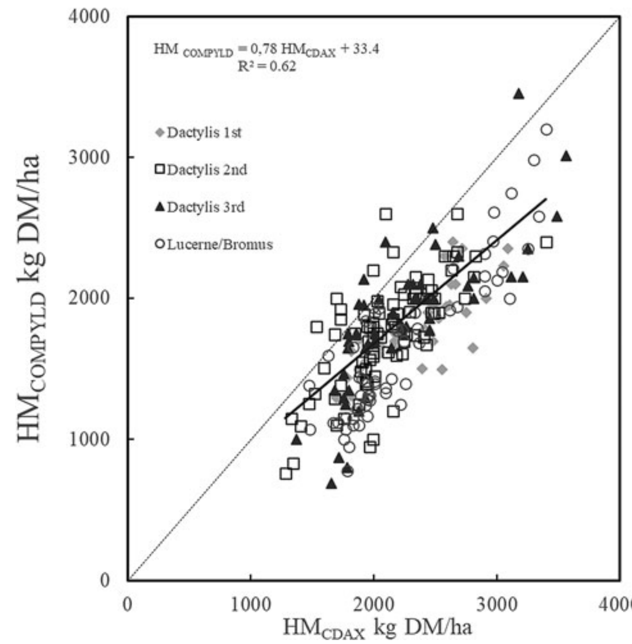

Figure 1. Relationship between herbage mass estimated by the pasture meter (CDAX) and the comparative yield method (COMPYLD) for Dactylis (1 year old: ◆, $n = 36$; 2 years old: □, $n = 83$; 3 years old: ▲, $n = 52$), Lucerne-bromus (○, $n = 60$).

When GR was averaged over the grazing area, the variability in weekly GR was somewhat reduced but differences between methods remained difficult to assess due to high variability [$GR_{CDAX} = 0.18\ (\pm 0.13)\ GR_{COMPYLD} + 26.3\ (\pm 2.3)$ ($R^2 = 0.03$, $n = 66$, CV = 58%, RMSE = 18.9; Fig. 5)]. Weekly GR can have large inherent errors because changes in HM over a week can be small compared to the error incurred in the two consecutive HM determinations. For that reason, moving averages were estimated (Fig. 5). Using 3-weeks moving averages reduced variability in GR substantially, with values ranging from 9 to 62 kg DM/ha/d (Fig. 5). Thus averaged, CDAX and COMPYLD yielded similar GR up to 35 kg DM/ha/d [$GR_{CDAX} = 0.51\ (\pm 0.12)\ GR_{COMPYLD} + 15.7\ (\pm 1.3)$ ($R^2 = 0.22$, $n = 49$, CV = 25.5%, RMSE = 9.1 kg DM/ha/d)], and somewhat higher GR in CDAX above 35 kg DM/ha/d.

To compare GR estimated by CDAX, COMPYLD and SAT, data was averaged per month for the whole grazing area. Differences among methods had no discernible pattern: SAT estimations differed from CDAX in February, July, September, November and December, and from COMPYLD in September and November (Table 2). Whereas CDAX GR estimations differed from COMPYLD for February and June.

To further assess whether systematic differences in estimated GR exists between methods, weekly average GR of the grazing area were accumulated over the 18-months of study (April 2017–October 2018). CDAX and COMPYLD yielded the same cumulative GR: 17 162 *v.* 17002 kg DM/ha, respectively (Fig. 6). SAT-derived ANPP yielded very similar values only 4 and 7% lower than CDAX and COMPYLD, respectively, considering the period where determinations by SAT were performed (June 2017 to July 2018).

Monitoring frequency and average downtime

Due to clouds, useful Sentinel-2 imagery was available on average every 23 ± 10 days. Thus, SAT had 65% downtime relative to the aim of weekly determinations. CDAX had a higher frequency of

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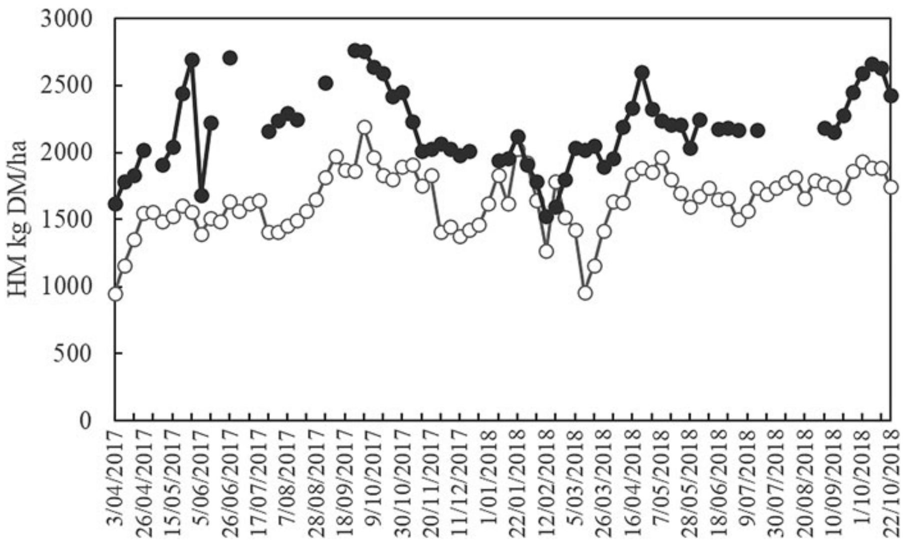

Figure 2. Weekly evolution over the 18-months experimental period (April 2017–October 2018) of the average herbage mass of a grazing area with 13 paddocks and 42 ha estimated by pasture meter (●, CDAX) and by the comparative yield method (○, COMPYLD).

measurements, with an average of one every 10 ± 4.5 days. Thus, relative to the aim of weekly determinations, CDAX had a 17% downtime, mostly due to break down of the quad-bike engine, or high rainfall events hindering access to paddocks. COMPYLD had no downtime period and provided consistent weekly measurement as planned without any infrastructure trouble preventing to carry out measurements (Table 2).

SAT monitoring was ten times faster than COMPLYD and twice as fast as CDAX respectively. However, it was the method less reliable, because of frequent lack of high-quality images due to cloudy weather.

Annual cost of monitoring the grazing area

For the experimental conditions of the present study, the cost of monitoring a grazing area of 42 ha with 13 paddocks was US$/ha/year 42.10 and 71.80 for CDAX and COMPYLD, respectively (Table 3). This reflected that labour requirement was 3.1 times lower in CDAX than COMPYLD (80.5 *v.* 286 h/year, respectively), which offset the amortization/depreciation and maintenance and fuel costs associated with CDAX (Table 1). SAT resulted the cheapest monitoring option when assuming that it is provided virtually free of charge to the farmer, as is the case in Uruguay for MODIS images (http://www.eleche.com.uy/cooperarios/productores-seguimiento-forrajero-satelital?es). For SAT cost to become comparable to CDAX's, the price of accessing and processing images, plus implementing the algorithm to estimate ANPP (Eqns 1–2), would have to be US$/ha/year 34. This is relatively high compared to current remote sensing services offered by commercial companies.

Discussion

Differences between methods in estimated herbage mass

Paddock HM estimated by CDAX was 22% higher than HM estimated by COMPYLD, throughout the experimental period and in all pasture types (Figs 1, 2 and 3). Averaged over the entire grazing area, the difference in estimated HM by CDAX *v.* COMPYLD ranged from 1138 to −119 kg DM/ha, with smaller differences occurring during summer (Fig. 2) when water deficit restricted HM (Figs 1 and 3). The reason underlying the discrepancy between methods is unclear.

Differences in accuracy (i.e. systematic variation or bias) in the calibrations of either COMPYLD or CDAX could have given rise to the difference between methods. However, both COMPYLD

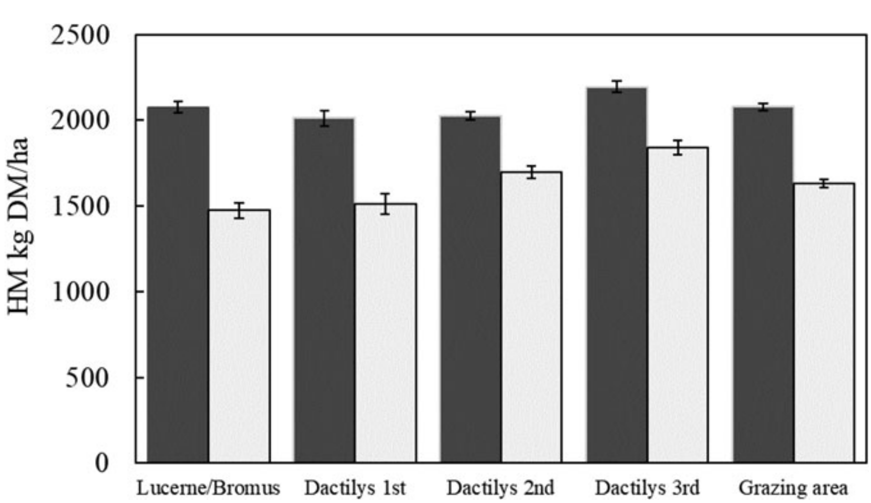

Figure 3. Average herbage mass and SEM over the 18-months experimental period (April 2017–October 2018) estimated by either the pasture meter (▬, CDAX) or comparative yield method (▬, COMPYLD) for Dactylis at 1, 2 or 3 years old, and in Lucerne-Bromus pastures of a grazing area of 42 ha (Tukey, $P < 0.05$).

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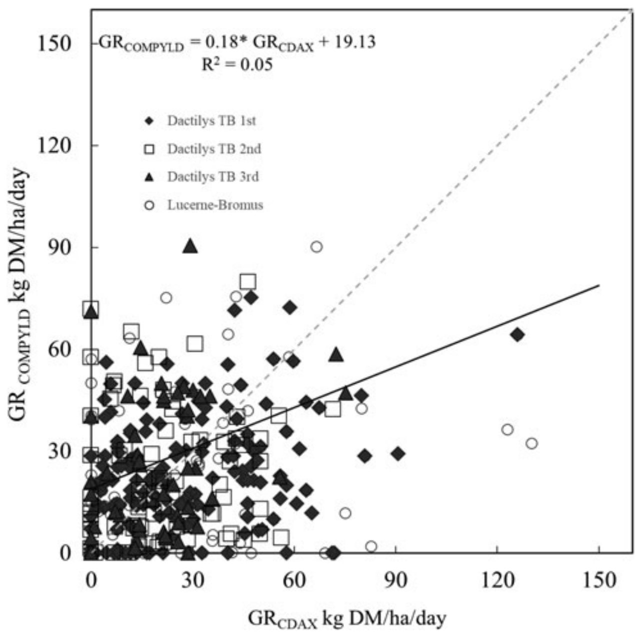

Figure 4. Relationship between weekly growth rates of individual paddocks (2–4 has) derived from herbage mass estimated by the pasture meter (CDAX) and the comparative yield method (COMPYLD), for Dactylis (1 year old: ◆, $n = 36$; 2 years old: □ = 86; 3 years old: ▲ = 52), Lucerne-Bromus (○ $n = 150$).

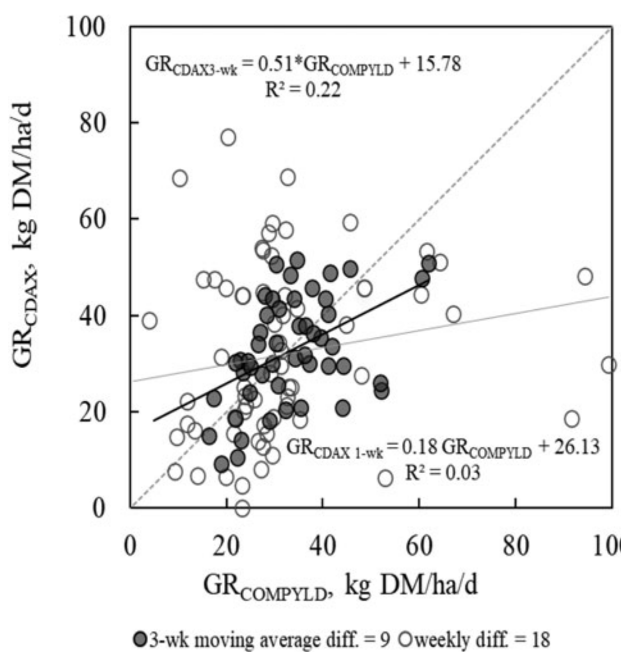

Figure 5. Relationship between growth rates of a grazing area of 13 paddocks and 42 ha estimated for 18 months (April 2017–October 2018) by the pasture meter (CDAX) and the comparative yield method (COMPYLD). Open symbols (○) are weekly averages differences, closed symbols (●) represent differences between methods on 3-weeks moving averages, (---) represents the $GR_{CDAX} = GR_{COMPYLD}$ relationship.

(this study, Supplementary Fig. S1) and CDAX calibrations (Waller, 2020) had similar mean absolute error (about 420 kg DM/ha) and were checked for bias *via* analysis of residuals (COMPYLD) and cross-calibration (CDAX). In consequence, it is difficult to ascribe the observed difference between methods

Table 2. Average (± SEM) growth rate per month (GR) and days between data collection for pasture meter (CDAX), the comparative yield method (COMPYLD) and the implementation of satellite pasture growth rate estimation (SAT) on a grazing area consisting of 13 paddocks and 42 ha

	Jul 2017	Aug 2017	Sep 2017	Oct 2017	Nov 2017	Dec 2017	Jan 2018	Feb 2018	Mar 2018	Apr 2018	May 2018	Jun 2018
GR kg DM/ha/d												
CDAX	24.1 ± 9.6 a	31.3 ± 6.4 a	23.0 ± 7.9 b	26.7 ± 4.5 a	38.1 ± 6.8 a	6.9 ± 8.4 a	27.4 ± 8.1 a	43.7 ± 9.2 a	23.3 ± 7.9 a	38.7 ± 4.9 a	29.5 ± 5.7 a	22.9 ± 6.1 a
COMPYLD	20.1 ± 11.1 a	26.1 ± 7.6 a	26.1 ± 5.9 b	32.4 ± 5.6 a	39.3 ± 6.3 a	17.2 ± 10.9 ab	31.7 ± 10.2 a	12.1 ± 9.6 b	11.8 ± 9.3 a	31.9 ± 6.2 a	34.0 ± 6.7 a	13.7 ± 7.5 b
SAT	33.1 ± 8.5 a	37.4 ± 7.4 a	63.0 ± 5.0 a	17.2 ± 6.8 a	17.4 ± 4.3 b	28.2 ± 2.9 a	17.5 ± 13.8 a	7.4 ± 10.3 b	7.7 ± 7.1 a	32.5 ± 8.7 a	36.2 ± 5.9 a	39.1 ± 9.5 a
Days between data collection												
CDAX	17	11	21	7	7	10	9	7	7	7	7	10
COMPYLD	7	7	7	7	7	7	7	7	7	7	7	7
SAT	na	33	45	35	13	18	20	12	10	20	20	20

GR estimations for CDAX and COMPYLD derived from herbage mass estimated.
Different letters indicate differences between methods for the same month for GR ($P < 0.05$).

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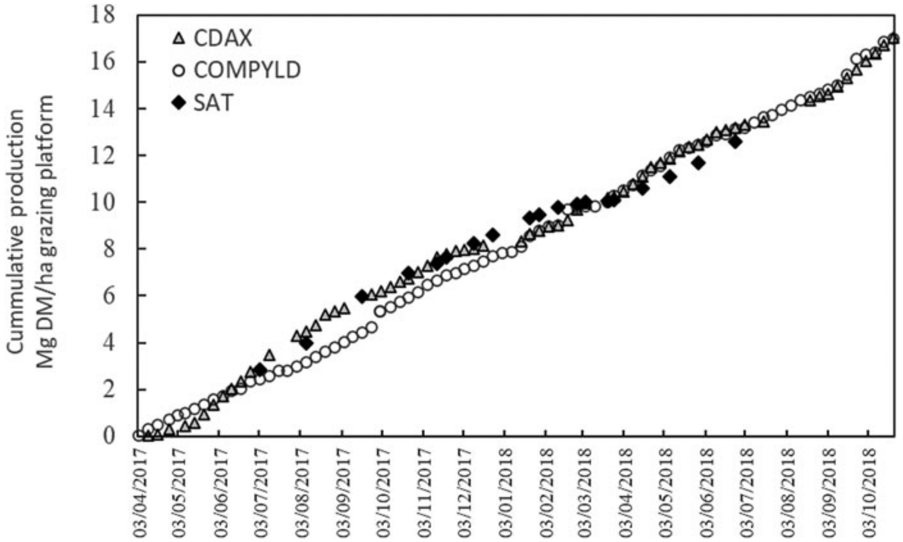

Figure 6. Cumulative production resulting from adding weekly growth rates of the whole grazing area consisting of 13 paddocks and 42 ha (period April 2017–October 2018) estimated by pasture meter (▲, CDAX), the comparative yield method (○, COMPYLD) and the implementation of satellite pasture growth rate estimation (◆, SAT).

to systematic errors incurred during calibration. However, bias might have occurred during visual assessments (see below).

So far, CDAX had only been compared to the rising plate meter method, giving similar HM estimation for pastures in New Zealand and Switzerland (Rennie *et al.*, 2009; King *et al.*, 2010; Schori, 2015; Hutchinson *et al.*, 2016). However, differences on HM estimations between methods are indeed frequent (e.g. Harmoney *et al.*, 1997; 't Mannetje, 2000, Lile *et al.*, 2001; Sanderson *et al.*, 2001; O'Donovan *et al.*, 2002 and citations therein), hence the recommendation for cross-calibration (Rayburn *et al.*, 2007).

Table 3. Economic valuation (US$/ha/year) considering investment on the pasture meter (CDAX) in contrast to hire a trained person to run the comparative yield method (COMPYLD) and the implementation of satellite pasture growth rate estimation (SAT) on the complete grazing area of 42 ha and 13 paddocks

	METHOD		
	CDAX	COMPYLD	SAT
Labour hours			
Monitoring, hours/week	1.5	5.0	0.5
Monitoring, hours/year	78	260	26
Training, hours/year	2	16	10
Information analysis, hours/week	0.5	1.0	1
Labour US$/hours	9.2	9.2	9.2
Annual cost US$/year			
Amortization[a]	411	–	–
Maintenance	112	–	–
Fuel	273	–	–
Labour cost US$/year			
Monitoring	717	2391	239
Information analysis	239	478	9
Training	18	147	92
Total annual cost			
US$/year	1770	3016	340
US$ ha/year	42.1	71.8	8.1

Total annual cost (US$/year) considering labour cost, fuel, maintenance and amortization of a quad-bike for CDAX according to hours (hours) of use.
[a]Includes quad-bike and CDAX annual depreciation as expressed on Table 1.

Frame (1993) mentions that the frequency of patches with high HM is often underestimated in COMPYLD. The 20 visual measurements per paddock used in the present study are deemed sufficient to estimate HM within ± 150 kg DM/ha (Hutchinson *et al.*, 2016) or ± 10% (Do Carmo *et al.*, 2020) of the true value for the observed CV (<30%). However, if the bias mentioned by Frame (1993) did occur, it would explain the lower HM estimated by COMPYLD. That visual methods are prone to bias is also mentioned by Lantinga *et al.* (2004). Indeed, a major advantage of CDAX is that the estimated HM is based on an extremely large number of observer-independent height measurements (>36 000 per paddock, in the present study).

Concordance among methods in estimation of pasture growth rate and production – the role of spatial and temporal integration to reduce uncertainty

For estimations of the weekly GR of individual paddocks, no clear difference between methods was evident. However, such a lack of statistically significant differences could be due to the very large variability (Fig. 4). Variation in weekly GR was indeed expected to be large because it is estimated from consecutive measurements of HM, each with substantial uncertainty ('t Mannetje, 2000). Lile *et al.* (2001), comparing the rising plate meter *v.* visual assessment to estimate HM, also found large uncertainty in estimated weekly GR. Nonetheless, when GR were integrated over the entire grazing area in three-weeks moving-averages, COMPYLD and CDAX yielded similar GR, at least up to 35 kg DM/ha/d. Such a reduction in uncertainty suggests that variation in GR was not systematic, and this spatially and temporally averaging multiple estimations cancelled out random fluctuations.

Above 35 kg DM/ha/d, CDAX appeared to estimate higher GR than COMPYLD (Fig. 5). This is consistent with the behaviour of HM estimations, as GR higher than 35 kg DM/ha/d were only obtained in paddocks with high pre-grazing HM, i.e. where the

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absolute differences in estimated HM in favour of CDAX were largest (Fig. 1).

Accumulating estimated grazing area GR over the 18-month experimental period yielded virtually the same productivity for CDAX and COMPYLD: 17162 *v.* 17002 kg DM/ha, respectively (Fig. 6). This further support the notion that, once random variation in estimated GR is reduced by integrating temporally (3-weeks) and spatially (entire grazing area), both methods provide a similar estimation of GR.

The same large variability observed in weekly GR of individual paddocks estimated by COMPYLD and CDAX was evident in daily GR estimated by SAT (data not shown). When averaged per month, differences in GR of the grazing area between SAT, CDAX and COMPYLD were sometimes detected (Table 2), but with no discernible pattern. The cause for such differences might be related to fact that the value of RUE and the relationship between NDVI and fPAR were both assumed invariant across pasture types and seasons (Chilibroste, 2009). However, it is known that at least RUE can be affected by soil moisture, fertilization, type of pasture and management (Piñeiro *et al.,* 2006). Yet, when integrated over several months (Fig. 6), differences between methods virtually disappeared, which suggests that assuming invariant RUE and NDVI-fPAR relationship would be valid to estimate annual average GR.

Implications of method selection for decision making in grazed dairy systems

Timely grazing decision making is considered prerequisite for efficient pastoral dairy systems, particularly in non-subsidized economies that base their competitiveness in low cost per unit product (Fariña and Chilibroste, 2019). Different grazing management decisions require information at different spatial and temporal scales and are therefore differently affected by the accuracy and precision of HM and GR estimations (Insua *et al.,* 2019).

Our results show that the 22% lower estimated HM estimated by COMPYLD than CDAX (Fig. 1) would need to be taken into account when defining the nominal HM target of the grazing area of a dairy farm, i.e. the average HM of all paddocks in the system, sometimes referred to as 'pasture cover'. Likewise, the definition of the size of daily grazing strips assigned to animals, as well as of target nominal post-grazing HM residual, would also need to be adjusted depending on whether the grazing area is monitored *via* COMPYLD or CDAX (*cf.* Lile *et al.,* 2001). Conversely, paddock selection in wedge plots, the timing and size of set-aside areas for haylage production when pasture growth exceed animal demand, or the triggering of reserves use to supplement animals when pasture growth cannot meet animal demand are all decisions largely independent of whether COMPYLD or CDAX are used for grazing area monitoring because both methods provide similar estimation of spatially- and temporally-averaged GR (Fig. 2).

Differences in reliability and costs can be decisive when selecting a monitoring method

Differences among methods in monitoring frequency, and thus reliability, is acknowledged as relevant as those in accuracy or precision for implementing HM and GR monitoring aimed at guiding short-term (weekly) grazing decisions (Thomson *et al.,* 2001). At the current ratio of labour-to-CDAX price, COMPYLD resulted costlier (Table 1), something that has been previously reported (*cf* King *et al.,* 2010; Tarrant and Armstrong, 2012; Schori, 2015). However, the estimated difference in cost would need to factor in production losses due to ill-timed grazing management decisions arising from lacking HM and GR data during periods of downtime of CDAX. These typically are caused by quad-bike or CDAX breaks downs, or access limitation on wet pastures (King *et al.,* 2010). At the very least, investment on CDAX-based monitoring systems should be made along improvements in paddock access infrastructure to minimize time between measurements and maintenance costs, and an alternative monitoring strategy must be in place for periods of downtime.

In comparison, SAT-based estimations appear as an interesting option to combine measurements at high spatial resolution and low cost (Table 3). However, the temporal frequency achieved in the present study would have severely limited the possibility of consistently making timely decisions due to the lack of both HM data and images during cloudy periods. In the present study, SAT exhibited constraints preventing its routinary use for effective short-term (weekly) decision-makings due to gaps in imagery and no estimation of HM. In principle, the high spatial resolution of SAT and the speed of CDAX could be combined to develop better decision-making.

The recent implementation of algorithms to estimate HM from Sentinel images (e.g. Chen *et al.,* 2021) as well as improvement in the frequency of images gives hope that SAT-based monitoring could be an option in the future.

Conclusions

CDAX estimated consistently higher HM than COMPYLD. Estimated weekly GR of individual paddocks were highly variable in both methods, as well as in SAT, largely because of random variation. When integrated temporally in three-weeks moving averages and spatially over all paddocks of the grazing area, GR variability was substantially reduced and showed high correspondence between methods. Management decisions directly based on nominal HM, such as target HM of the grazing area or daily strip area, need to be adjusted depending on the method used to monitor HM. Decisions based on HM temporal trends or GR, such as timing and size of set-aside areas for mechanical harvest or use of reserves to supplement animals, would in principle be unaffected by the monitoring method. Investing on a CDAX, instead of using COMPYLD, would be advantageous for farms with high labour costs. However, farmers should contemplate downtime period, as well as additional investment on paddock accessibility infrastructure to minimize maintenance and reparations costs.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859623000333.

Authors' contributions. GO participated in experiment design, performed the field experiment, analysed the results, promoted data analysis discussions, wrote the original draft and revised versions of the manuscript. PC conceived, designed, obtained funding, administrated the project, supervised field experiments, results analyses and participated in data analysis discussions. JMG performed the field experiment and participated in data analysis discussions. AW participated in experiment design, performed the field experiment and participated in data analysis discussions. SRF and FL conceived, designed, supervised field experiments and participated in data analysis discussions. All authors reviewed the manuscript and approved the final version of the manuscript.

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