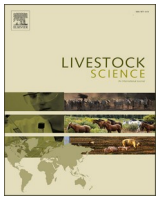
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Characterizing inter-individual responses of dairy cows to concentrate reduction

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HIGHLIGHTS

- Dairy cows use diverse strategies to cope with concentrate reduction.
- Access to base-ration intake flexibility limits milk yield decline.
- Energy deficits are offset by intake, milk loss or body reserves.
- Individual adaptation profiles vary widely and shift over time.
- Precision feeding requires predicting cows' adaptive capacity.

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ABSTRACT

Background and objectives: In dairy systems, concentrate allocation is commonly based on milk yield, days in milk and parity, assuming homogeneous responses among cows with similar characteristics. We hypothesized that cows differ in their short-term adaptive strategies when concentrate supply is reduced. The objective was to characterize inter-individual variability in milk yield and feed intake responses following a decrease in concentrate allowance.

Data collection: Sixty Holstein cows (one-third primiparous) were fed a common balanced base ration delivered individually via electronic weighing troughs and received concentrate through an automatic feeder. Each 6-week sequence comprised 3 weeks at 4 kg/d concentrate (**C4 phase**) followed by 3 weeks at 1 kg/d (**C1 phase**); the sequence was repeated three times. Cows were assigned to one of two treatments: **FLEX** (ad libitum access to the base ration) or **FIX** (base ration intake during C1 limited to the individual average intake recorded during the preceding C4 phase).

Research methods: Individual response profiles were defined using predefined quantitative thresholds established by an expert group. Compensation in base ration intake was expressed as kg additional base ration per kg concentrate reduction and classified as **B0** (<0.30), **B+** ($0.30 \leq B+ \leq 0.80$), or **B++** (>0.80). Milk yield response was expressed as kg milk change per kg concentrate reduction and classified as **M0** (>-0.30), **M−** ($-0.80 \leq M- \leq -0.30$), or **M−−** (<-0.80).

Results: With an average decrease of 2.40 kg DM/d concentrate supply, FLEX cows increased base ration intake by 1.35 kg DM/d and decreased milk yield by 1.24 kg/d while FIX cows maintained base ration intake (-0.08 kg DM/d) and decreased milk yield by 2.43 kg/d. Milk response profiles were equally distributed in FLEX cows whereas most FIX cows exhibited moderate to high milk losses. Marked variability was observed in both intake compensation and milk responses within treatments.

Contributions: Access to base ration modulates milk response to concentrate reduction and provides evidence of substantial inter-individual variability in short-term adaptive strategies. By proposing quantitative response profiles combining intake and milk changes, it contributes a phenotyping framework for identifying response profiles that could eventually support the development of individualized feeding approaches.

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Introduction

The widespread use of partially mixed rations (**PMR**) in large herd dairy farms, in which cows receive a base ration at the feed trough supplemented with individualized concentrate, reflects a broader shift towards precision feeding in modern dairy systems. This approach has expanded in many countries alongside the adoption of automatic concentrate feeders, enabling individual concentrate allocation based on factors such as milk production, parity, and stage of lactation (**DIM**). In France, for example, the proportion of dairy farms equipped with automatic concentrate feeders increased from 28.0% of 772 surveyed farms in 2015 to 56.2% of 856 surveyed farms in 2023 (Allain et al., 2015; Nicolas and Allain, 2024), underscoring the move towards more technology-driven dairy management.

While automatic concentrate feeders enable cow-level concentrate allocation, their effectiveness ultimately depends on how individual cows respond to changes in concentrate supply. Previous studies have shown substantial inter-individual variability in dairy cows' responses to nutritional challenges, including differences in feed intake regulation, production responses, and energy balance adjustments (Faverdin et al., 1991; Gaillard and Abarnou, 2024). However, this variability is rarely incorporated into feeding decisions. Several studies have shown that, when individual concentrate allocation is adjusted without altering the total amount of concentrate distributed per group, animal performance, economic, and environmental outcomes can be similar to those achieved with total mixed ration (**TMR,** Pardue et al., 1975; Yan et al., 1998). These results highlight that individual concentrate feeding alone does not guarantee improved efficiency unless cow-level adaptive responses are explicitly considered.

Dairy cows can rely on multiple mechanisms to adapt to a reduction in concentrate supply, including adjustments in feed intake at the trough, mobilization of body reserves, and changes in milk production. The relative contribution of these mechanisms may differ substantially among cows. Some animals primarily compensate for reduced energy supply through increased feed intake, whereas others may maintain production by mobilizing body reserves or, conversely, reduce milk synthesis to preserve energy status. Understanding this diversity of adaptive strategies is essential for improving the biological basis of precision feeding approaches.

However, current decision-support tools used on farms primarily rely on milk production responses and economic criteria to guide concentrate allocation. For example, the Dynamic Feeding Module (DLM) implemented in Lely milking robots automatically adjusts concentrate supply according to the individual milk response of each cow, while accounting for milk price, concentrate cost and milk composition (fat and protein content) to optimize economic return rather than maximize milk production (André et al., 2009 and 2010). Such systems represent an important step toward precision feeding. However, they do not explicitly incorporate other adaptive mechanisms that may influence cows' responses to concentrate restriction, such as compensatory changes in basal ration intake or body reserve mobilization.

Before these additional adaptive mechanisms can be incorporated into individualized feeding models, it is necessary to determine whether inter-individual variability in response to concentrate reduction is sufficiently structured, biologically interpretable, and potentially repeatable to support the identification of meaningful response profiles. Previous studies have acknowledged that cows differ in their responses to nutritional challenges, but these differences are often treated as random effects in statistical models rather than explicitly characterized and classified. As a result, little information is available on how cows differ in their short-term capacity to compensate for a reduction in concentrate supply through changes in feed intake and milk production, particularly under controlled conditions where access to the base ration is either flexible or constrained. In this context, restricting access to the base ration can be used as an experimental tool to constrain one adaptive pathway (increased feed intake) and thereby reveal how individual cows differ in their short-term compensation strategies following concentrate reduction.

The objective of this study was therefore to characterize the variability and structure of short-term responses in milk yield and feed intake among dairy cows following a reduction in concentrate supply. The analysis focused specifically on concentrate reduction, as this scenario is of particular interest to dairy producers aiming to reduce feed costs while maintaining production. Rather than evaluating an individualized feeding strategy, the study aimed to establish a phenotyping framework based on predefined response profiles describing cows' adaptations in milk yield and base ration intake. We hypothesized that (1) cows with similar production level and parity differ in their short-term responses in milk yield and base ration intake to a reduction in concentrate supply; (2) cows with restricted access to the base ration compensate for reduced concentrate supply primarily by decreasing their milk production whereas cows with ad libitum access will express a broader range of compensatory responses involving both intake and production; and that (3) the distribution of response profiles differs significantly between cows with flexible versus fixed access to the base ration.

MATERIAL AND METHODS

The experiment was conducted from February 2022 to July 2022 at the experimental dairy farm of Trinottières (Montreuil-sur-Loir, France). All procedures involving animals complied with French regulations for animal care and use in agricultural research, in accordance with Directive 2010/63/EU on the protection of animals used for scientific purposes, as transposed into French law. The study was conducted within the framework of routine herd management procedures at the experimental farm and did not require specific ethical approval under the applicable French regulations.

Animals and housing

The experiment involved 60 Holstein dairy cows, including 20 primiparous cows, with an average DIM of 109 ± 37 at the start of the trial (Table 1). Cows remained in the experiment for 5.5 months.

Cows were housed in a free-stall barn with one cubicle per cow and 42 electronic weighing troughs (Controlling and Recording Feed Intake, BioControl AS, Norway), providing ad libitum access to the base ration and ensuring that trough availability was not limiting for feed intake. Individual access to troughs was controlled using RFID identification. Cows were milked twice a day, at 0630 h and 1630 h, in a rotary milking parlor (DeLaval, Tumba, Sweden).

Feeding system

All cows received a common base ration, distributed once daily at the feed troughs. The base ration consisted of a mixture of forages and concentrates (22%) and contained (in % DM): 56.9% corn silage, 16.0% ryegrass silage, 5.00% ryegrass haylage, 21.0% rapeseed meal, and 1.10% mineral-vitamin supplements (Table 2). The base ration provided 0.91 UFL/kg DM (UFL: feed unit for lactation, unit of net energy defined as the net energy content of 1 kg of standard barley; for reference, the net energy required to produce 1 kg of standard milk corresponds to approximately 0.42 UFL, INRA, 2018) and 81 g PDI/ kg DM (PDI: protein truly digestible in the small intestine, according to the French INRA feeding system; INRA, 2018). The base ration was formulated to meet the maintenance and production requirements of mid-lactation cows producing approximately 35 kg of milk per day without additional concentrate supplementation. Consequently, the extra concentrate supplied through the automatic feeders represented a nutritional supplement above the basal ration and created distinct levels of energy supply during the C4 and C1 phases.

In addition to the base ration, cows received an extra energy

Table 1
Baseline characteristics of the four experimental groups used for cow allocation before the start of the trial. Values correspond to measurements collected during the two weeks preceding the experiment and are presented as mean ± SD for continuous variables.

	FLEX_1	FLEX_3	FIX_2	FIX_4
Number of cows	15	15	15	15
Primiparous, %	33	33	33	33
Average lactation rank	2.5 ± 1.5	2.3 ± 1.4	2.1 ± 1.4	2.5 ± 1.3
DIM, d	112 ± 40	114 ± 38	109 ± 37	118 ± 36
Average milk yield, kg/d	35.0 ± 6.3	35.7 ± 5.7	35.6 ± 7.7	35.5 ± 7.0
Average fat in milk, g/kg	39.3 ± 4.7	42.2 ± 4.5	41.5 ± 4.6	39.7 ± 3.9
Average protein in milk, g/kg	32.0 ± 2.2	32.6 ± 2.3	32.5 ± 2.4	32.5 ± 2.1
Average intake at trough, kg/d	54.7 ± 3.1	56.0 ± 2.4	55.8 ± 3.2	57.6 ± 3.4
Average total dry matter intake, kg/d	26.0 ± 3.1	26.2 ± 2.3	26.5 ± 3.2	26.6 ± 3.4
Average body weight, kg	671 ± 69	678 ± 47	664 ± 82	690 ± 75

DIM = days in milk; FIX = cows with restricted access to the base ration; FLEX = cows with ad libitum access to the base ration.

Table 2
Ingredient and nutrient composition of the base ration fed to all cows.

Component	Value
Ingredient composition	
Maize silage, % DM	56.9
Ryegrass silage, % DM	16.0
Ryegrass haylage, % DM	5.0
Rapeseed meal, % DM	21.0
Mineral-vitamin supplement, % DM	1.1
Nutrient composition	
Crude protein, %DM	13.5
Crude fiber, %DM	18.3
NDF, %DM	41.3
Total starch, %DM	16.5
Net energy, UFL/kg DM[1]	0.91
PDI, g/kg DM	81.0
RDP balance, g/kg DM[2]	0.00

[1] 1 UFL = feed unit for lactation equivalent to 1,700 kCal or 7.11 MJ of net energy for lactation (INRA, 2018),
[2] RDP = Rumen Degradable Protein balance (INRA, 2018).

concentrate supplied individually through three automatic concentrate feeders (DeLaval DAC stalls, Tumba, Sweden). This concentrate contained 17% crude protein and 87.5% of DM (Table 3).

The ingredient and nutrient composition of the base ration and concentrate were identical across feeding treatments (FLEX and FIX) and across experimental phases; only the quantity of concentrate supplied via the automatic feeders differed between the C4 and C1 phases.

Experimental design and treatments

The trial followed a repeated-measures design consisting of three successive sequences (Fig. 1). Each sequence lasted 6 weeks and included:

- a 3-week high extra concentrate phase (**C4 phase**), and
- a 3-week low extra concentrate phase (**C1 phase**).

During the C4 phase, cows received up to 4 kg/cow per day of extra concentrate (as-fed basis) via the automatic feeders. During the C1 phase, this allowance was reduced to 1 kg/cow per day (as-fed basis).

Table 3
Chemical composition of feed ingredients used in the base ration and of the concentrate.

	Maize silage	Ryegrass haylage	Ryegrass silage	Rapeseed meal	Concentrate[1]
DM, %	36.5	39.7	40.0	88.0	87.5
Ash, g/kg DM	34.0	88.0	79.0	79.6	84.6
Organic matter, g/kg DM	966	912	921	920	915
Crude protein, g/kg DM	60.0	102	92.0	378	200
Crude fiber, g/kg DM	214	302	203	149	113
Total starch, g/kg DM	330			63.0	276
Total fat, g/kg DM	24.0	20.8	21.0	20.5	30.5
NDF, g/kg DM	430	562	401	356	359
ADF, g/kg DM	232	310	209	197	132
ADL, g/kg DM	22.0	28.0	16.0	87.3	37.0

[1] Concentrate composition (% of DM, NOBIAECO 17 TR is a commercial concentrate blend formulated for dairy cows (17% crude protein), averages over 3 periods): wheat bran (23.4); Amyplus 416 Nestlé - a cereal-based starch-rich feed ingredient derived from processed grains (19.8); sunflower meal (de-oiled,11.3); by-products from the production of amino acids and vinasses (10.0); wheat or barley (8.35); maize (8.00); dried sugar beet pulp (6.67); grape pulp (3.30); Proteinal – a commercial protein supplement based on processed plant protein sources (4.53); sunflower Hi-Pro (4.05); corn gluten feed and distillers grains and solubles from cereal processing (2.00); calcium carbonate (1.41); molasses (1.00); Px Rum Valea (0.55); ammonium sulfate (0.35); sodium chloride (0.57). Net energy from concentrate: 1.03 UFL/kg DM.

These quantities refer exclusively to the extra concentrate supplied via the automatic feeders and were applied uniformly to all cows.

These concentrate levels were selected to create a substantial but realistic reduction in concentrate supply representative of commercial PMR systems equipped with automatic concentrate feeders. The objective was not to compare specific concentrate-feeding strategies, but to generate a nutritional challenge large enough to reveal inter-individual differences in adaptive responses while maintaining adequate nutrient supply and animal welfare.

The repeated-sequence design was chosen to expose cows to several standardized concentrate-reduction challenges throughout lactation. No wash-out period independent of the subsequent C4 phase was included. Instead, each 3-week C4 phase was intended to re-establish a common feeding condition before the following C1 challenge.

At the start of the experiment, the 60 cows were allocated into four balanced groups of 15 cows. Each group included both primiparous and multiparous cows (Table 1). Group allocation was performed using a balancing procedure based on parity, DIM, milk yield, milk composition (fat and protein content), body weight (**BW**), and total dry matter intake (**DMI**) measured during the two weeks preceding the experiment (Table 1). The four groups were therefore comparable in terms of production level and physiological status at the start of the experiment.

The feeding treatments were assigned at the group level. Groups 1 and 3 were assigned to the FLEX treatment, whereas groups 2 and 4 were assigned to the FIX treatment (Fig. 1). To avoid confounding treatment effects with environmental or temporal factors, groups 3 and 4 entered the experiment three weeks after groups 1 and 2. All groups followed the same experimental structure, and cows within a given group transitioned simultaneously between C4 and C1 phases.

In the FLEX treatment, cows had ad libitum access to the base ration

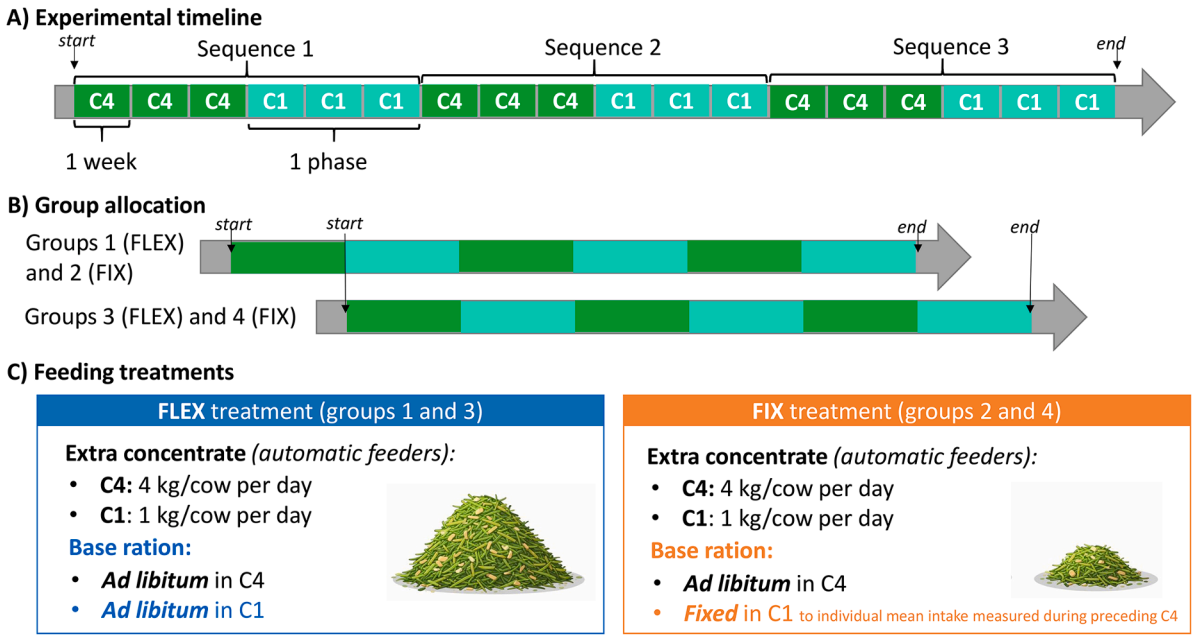


Fig. 1. Experimental design of the study. Cows were assigned to two feeding treatments (FLEX and FIX) and exposed to three successive 6-week sequences, each comprising a 3-week high extra-concentrate phase (C4) followed by a low extra-concentrate phase (C1). In the FLEX treatment, cows had ad libitum access to the base ration throughout the experiment, whereas in the FIX treatment, access to base ration was restricted during the C1 phases.

throughout the experiment, allowing voluntary adjustment of base-ration intake during the C1 phases. In the FIX treatment, cows had ad libitum access to the base ration during the C4 phases only. During each subsequent C1 phase, base-ration intake was restricted to the individual average intake recorded during the last two weeks of the preceding C4 phase. Base-ration restriction was calculated for each cow in kg DM/day based on the dry matter content of the base ration.

Measurements

The base ration was prepared daily using a mixer wagon to ensure a homogeneous mixture and was distributed each morning after milking. The DMI was calculated based on DM content measured from daily samples of the forages and biweekly samples of the concentrate. The DM content was updated weekly to account for any changes.

Feed intake at the troughs was continuously monitored. These troughs recorded the initial and final weights of the ration during each visit, allowing precise measurement of feed intake per visit per cow. The total daily base ration intake for each cow was calculated by summing the amounts consumed during all visits over a 24-h period and was then converted to DMI using the weekly DM measurements of the feed components.

Extra concentrate was distributed via automatic feeders continuously throughout the day. Concentrate delivery occurred when cows voluntarily visited the feeders and was dispensed in small portions (approximately 40 g per drop) until the individual daily allowance was reached. The timing and mode of distribution were identical for all cows; only the maximum daily allowance differed between experimental phases (4 kg/cow per day during C4 phases and 1 kg/cow per day during C1 phases). No additional temporal restrictions were applied to concentrate access. Automatic feeders were calibrated regularly according to the manufacturer's recommendations. Milk yield was recorded individually at each milking and summed on a daily basis.

Milk samples were collected weekly from 4 milkings (Monday evening, Tuesday morning, Thursday evening, and Friday morning). Body weight was measured automatically twice daily after milking using a dynamic scale that identified the cow via RFID (Delpro® management software, DeLaval, Sweden). Body condition score was assessed every 14 days by two trained evaluators using the scoring system of Bazin et al. (1984), ranging from 0 (very thin) to 5 (very fat).

Chemical analysis

Milk samples were analyzed individually (i.e., 4 samples per cow per week) for fat and protein contents. Feed samples were ground with a 3-blade knife mill through a 0.80-mm screen. Feed samples were analyzed for DM (standard NF V18–109, October 1982), ash (standard NF V18-101, October 1977 - incineration at 550°C for 5 h in a muffle furnace), and CP (Kjeldahl method, standard NF EN ISO 5983–1, December 2005). Neutral detergent fiber, ADF, and ADL, were determined according to the method of Van Soest (1967) (standard NF V18-122, October 2013). Starch content was determined by polarimetry method (standard NF ISO 6493, November 2011).

Calculations

The net energy of milk (**NEM**) was calculated according to the following equation (INRA, 2018):

$$\text{NEM} = \text{Milk Yield} \times [0.42 + 0.0053 \times (\text{Fat} - 40.0) + 0.0032 \times (\text{Prot} - 31.0)]$$

where NEM is expressed in UFL/d (then converted in MJ/d, conversion factor of 1 UFL = 7.11 MJ net energy), milk yield in kg/d, "Fat" is the milk fat content in g/kg and "Prot" the true milk protein content in g/kg.

Net energy intake (**NEI**, UFL/d) was calculated from individual daily dry matter intake and the net energy value of the diet, estimated from feed chemical composition according to INRA (2018), including corrections for digestive interactions related to diet composition (e.g., forage-to-concentrate ratio).

Energy requirements were calculated according to INRA (2018) as the sum of requirements for milk production, maintenance, growth, and gestation:

$$\text{Energy balance (UFL / d)} = \text{NEI} - (\text{NEM} + \text{Maintenance} + \text{Growth} + \text{Gestation})$$

Maintenance, growth, and gestation energy requirements were estimated using standard INRA (2018) equations based on BW, parity, and stage of gestation. The average weekly energy balance was calculated for each cow and sequence using weekly averages of intake and production variables.

Response calculations and profile definition

Responses to concentrate reduction. The first week of each phase (C1, C4) was considered as an adaptation period and was excluded from data analysis. Additionally, the last day of each phase, corresponding to the dietary transition, was removed.

For each cow-sequence, the response in milk yield and base ration intake to the reduction in concentrate supply was calculated as the change from the C4 phase to the subsequent C1 phase, expressed per kg of concentrate reduction, according to the following equation:

Response (milk yield or base ration intake) = (average response variable during C1 phase - average response variable during the preceding C4 phase) / (average concentrate intake during the preceding C4 phase - average concentrate intake during C1 phase).

Changes in DMI, milk yield, milk components, NEM, BW, BCS, and energy balance between the C4 and C1 phases were calculated as:

$$\text{Change} = (\text{average during C1 phase} - \text{average during preceding C4 phase})$$

Definition of response profiles. Response-profile thresholds were defined a priori by a multidisciplinary expert group including researchers, nutritionists, technicians, and dairy farmers. The objective was not to identify statistically optimal cut-points but to create biologically meaningful and practically interpretable response categories that could facilitate comparison among cows. Consequently, the proposed thresholds should be viewed as an initial phenotyping framework rather than definitive biological boundaries.

Changes in base ration intake per kilogram of concentrate reduction were classified as:

- B0 (no compensation): < +0.30 kg of additional base ration DMI per kg of concentrate removed
- B+ (moderate compensation): +0.30 to +0.80 kg
- B++ (high compensation): > +0.80 kg

Changes in milk yield per kilogram of concentrate reduction were classified as:

- M0 (no loss): > -0.30 kg of milk
- M- (moderate loss): -0.80 kg to -0.30
- M– (high loss): < -0.80 kg.

For cows in the FLEX treatment, individual response profiles were defined as combinations of base ration intake response (B0, B+, B++) and milk yield response (M0, M−, M−−), resulting in 9 possible response profiles (Fig. 2).

For cows in the FIX treatment, base ration intake could not increase during C1 phases by design; therefore, response profiles were defined solely based on milk yield responses (M0, M−, M−−), resulting in 3 possible profiles.

Each cow-sequence was assigned to one response profile based on its calculated responses.

Residual variability was summarized using the residual standard deviation (**RSD**), and further illustrated by the distribution of cow-

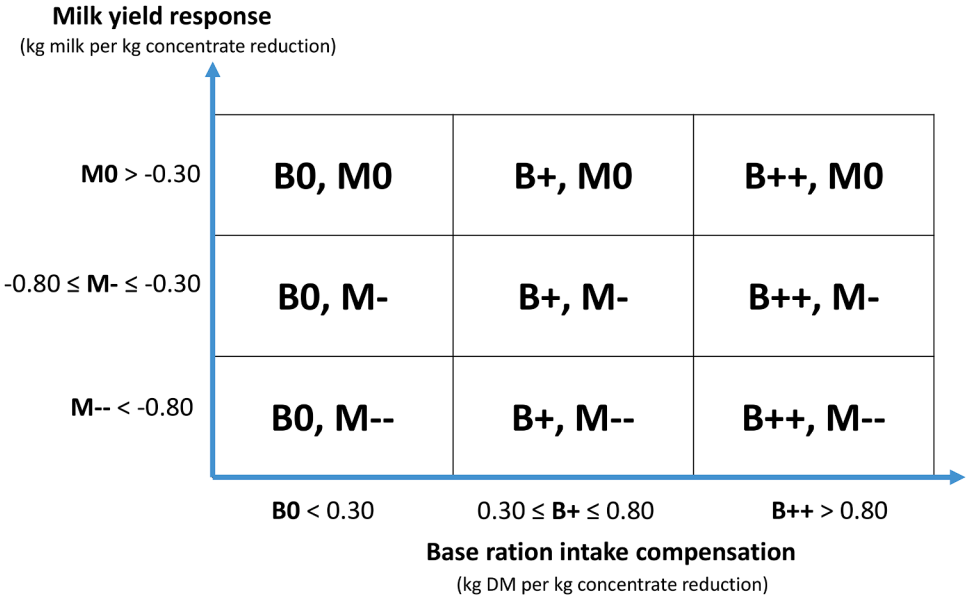


Fig. 2. Definition of response profiles following concentrate reduction. Response profiles were defined according to changes in base-ration intake (B0, B+, B++) and milk yield (M0, M−, M−−) following concentrate reduction. Each square of the 3 × 3 grid corresponds to one response profile.

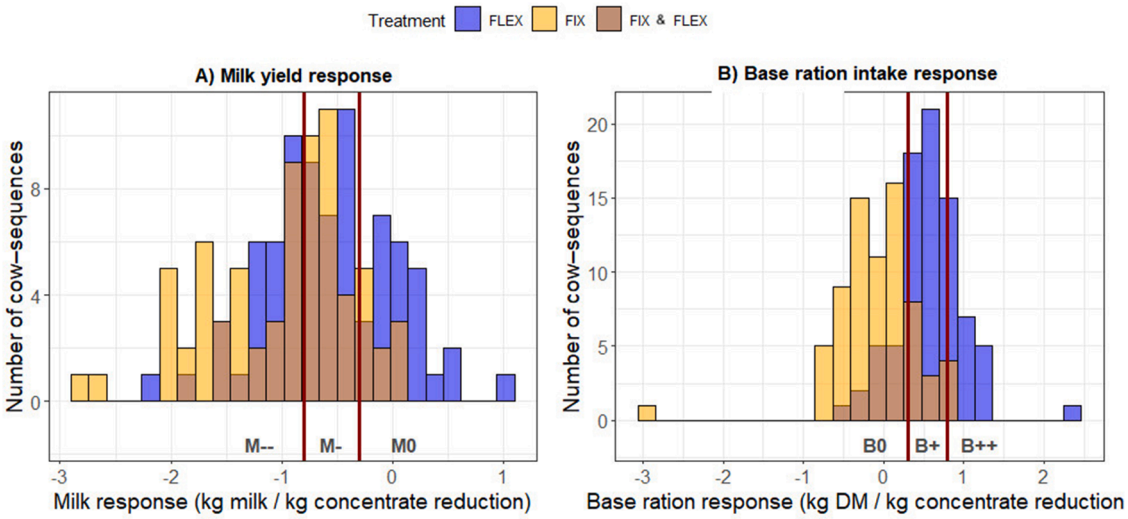


Fig. 3. Distribution of individual responses used to define response profiles following concentrate reduction. Vertical red lines indicate the thresholds used to classify milk-yield responses (A) and base-ration-intake responses (B). Histograms are shown separately for FLEX (blue) and FIX (orange) treatments; brown areas correspond to overlapping portions of the two distributions resulting from histogram transparency.

sequences among response profiles (Table 5). Response distributions were also visualized using histograms to assess the adequacy of the classification thresholds (Fig. 3).

Statistical analysis

The statistical analyses were carried out using R (Core Team, 2024). Effects were considered statistically significant when $P < 0.05$ and as a tendency when $0.05 \leq P < 0.10$. Sequence was systematically included as a fixed effect in all models to account for potential temporal and environmental variation across the experiment.

Linear mixed-effects models. Linear mixed-effects models were fitted using the lmer function from the lmerTest package (Kuznetsova et al., 2017). For all analyses, the initial models included feeding treatment (FIX vs. FLEX), parity (primiparous vs. multiparous), lactation stage at the start of the experiment (DIM, continuous), sequence (1, 2, or 3), experimental group (1 to 4), and selected two-way interactions (sequence × treatment, group × sequence, and treatment × parity) as fixed effects. Cow was included as a random effect to account for repeated measurements across sequences. The initial model can be written as:

$$Y_{ijklmno} = \mu + Treatment_i + Parity_j + DIM_k + Sequence_l + Group_m + Interactions + BaselineCovariate_n + Cow_o + \varepsilon_{ijklmno}$$

where Cow was fitted as a random effect and ε represents the residual error.

For the analysis of average responses during C4 phases, variables of interest (DMI, milk yield, milk composition, BW, NEM, and energy balance) were averaged separately for each of the three C4 phases. To account for baseline differences among cows, a covariate corresponding to the pre-experimental value of the analyzed variable (recorded the week preceding the start of the trial) was included in the model and centered within parity group.

For the analysis of responses to concentrate reduction, changes between each C4 phase and the subsequent C1 phase were analyzed. For most variables, the average value measured during the corresponding C4 phase was included as a covariate to adjust for baseline status before concentrate reduction. For base ration intake response and milk yield response expressed per kilogram of concentrate reduction, no baseline covariate was included because these variables already represented standardized responses.

Model simplification was performed using a stepwise procedure to remove non-significant fixed effects, while the feeding treatment was retained in all models regardless of significance.

Consistency of the individual response profiles across sequences. To assess the consistency of individual response profiles across sequences, each of the nine response profiles defined for FLEX cows was assigned a pair of coordinates (x, y) corresponding to its position in Fig. 2. For each cow, absolute differences in x and y coordinates between successive sequences were calculated and summed to quantify profile change over time.

A variable termed "Profile Change" was thus defined, taking a value of 0 when the cow maintained the same response profile between sequences, 1 when the profile shifted by one adjacent category (horizontal or vertical), 2 when the profile shifted by two categories, 3 when the profile shifted by three categories, and 4 for the largest possible shift (e.g., from (B0, M0) to (B++, M–)). This metric was used to quantify the stability or variability of individual response strategies across successive concentrate reduction challenges.

RESULTS

Final dataset. Out of the 180 potential cow-sequences (60 cows × 3 sequences), 28 sequences were excluded due to health issues (primarily lameness) that significantly affected concentrate intake. The remaining 152 cow-sequences were retained for the response-profile analyses (Table 5). For analyses requiring calculation of average responses between C4 and C1 phases, four additional sequences were excluded because they corresponded to cows with incomplete recordings (i.e., cows with only one fully recorded sequence). Consequently, 148 cow-

Table 4
Averages[1] of feed intake and production variables for both feeding treatments (FLEX and FIX) estimated either over the C4 phases or as the change between the C1 and C4 phases.

	Averages over C4[2] phase		RSD[6]	P-value	Change C1[2] phase – C4 phase		RSD	P-Value
	FLEX[3]	FIX[3]			FLEX	FIX		
DMI of concentrate, kg/d	3.17	3.15	0.18	0.62	-2.45	-2.42	0.05	0.04
DMI of base ration, kg/d	21.5	21.9	0.78	0.09	+1.35	-0.08	0.74	<0.01
Total DMI, kg/d	24.7	25.1	0.85	0.12	-1.10	-2.50	0.76	<0.01
Total ingested, MJ NE/d	155	157	4.79	0.14	-5.80	-11.8	4.16	<0.01
Milk yield, kg/d	32.8	33.0	1.36	0.08	-1.24	-2.43	0.98	<0.01
Milk fat, g/kg	40.2	40.4	1.17	0.50	+1.06	+1.44	1.41	0.57
Milk protein, g/kg	32.9	33.1	0.46	0.30	+0.01	-0.07	0.52	0.36
NEM[4], MJ NE /d	102	104	4.10	0.02	-2.73	-6.34	3.27	<0.01
BW (morning), kg	678	683	10.0	0.08	+7.54	+7.54	7.32	0.99
BCS[5], points	3.04	3.05	0.14	0.88	+0.10	+0.05	0.17	0.13
Energy balance, MJ NE /d	-5.08	-4.49	3.64	0.67	-4.46	-6.33	4.02	0.03
Response in base ration intake, kg/kg concentrate					+0.59	-0.05	0.39	<0.01
Response in milk, kg/kg concentrate					-0.50	-0.94	0.46	<0.01

[1] Estimated marginal means (EMMEANS) are presented to compare the effects of feeding treatments on the different variables of interest, while accounting for covariates, fixed effects, and random effects included in the models. These adjusted means allow for fair comparisons between treatments, regardless of imbalances or inter-individual variability
[2] C4: 3-week phases during which the cows received 4 kg of concentrate at the automatic concentrate feeders, C1: 3-week phases during which the cows received 1 kg of concentrate at the automatic concentrate feeders
[3] FIX: cows receiving a fixed quantity of base ration during C1 phase
[3] FLEX: cows receiving a flexible (ad libitum) quantity of base ration during C1 phase
[4] NEM: Net energy (NE) in milk
[5] BCS: body condition score
[6] RSD: residual standard deviation.

sequences were available for the analyses of quantitative responses.

For the analyses of profile stability across sequences (Table 6), cows needed to have at least two valid sequences. Therefore, 6 cows (all from the FIX treatment), representing 18 potential cow-sequences, were excluded because only one sequence remained available after data filtering. Fourteen cows had one missing sequence but were retained for stability analyses using their remaining valid sequences.

Average responses during C4 phases. During C4 phases, there were minimal differences between the FIX and FLEX cows. Both treatments had similar DMI of concentrate and base ration, with the FIX cows tended to consume slightly more base ration (0.4 kg/d, P = 0.09, Table 4). Milk yield and milk composition (fat and protein contents) were also nearly identical between the treatments. This resulted in similar NEM with an average of 102 MJ/d/cow for FLEX cows and 104 MJ/d per cow for FIX cows (Table 4). The BW, BCS, and energy balance showed no significant differences between feeding treatments, and the energy balance remained slightly negative for both groups (Table 4).

Average responses subsequent to the concentrate reduction. FLEX cows were able to partially compensate for the 2.45 kg DM/d per cow reduction in concentrate intake by increasing their base ration intake by 1.35 kg DM/d per cow. They also exhibited a 4.46 MJ/d/cow decrease in calculated energy balance, which may indicate a greater contribution of body-reserve mobilization. As a result, the reduction in milk yield remained limited to 1.24 kg/d/cow, corresponding to a decrease of 2.73 MJ/d per cow in net energy produced in milk (Table 4). Comparatively, when cows could not compensate the 2.42 kg DM/d per cow reduction in concentrate intake by an increase of base ration (FIX cows), they compensated by a more important decrease in milk yield (2.43 kg/d per cow, 6.34 MJ/d per cow in net energy in milk; Table 4) and experienced a larger deterioration in calculated energy balance (-6.34 MJ/d). Those observations were confirmed by the difference in the averaged responses in milk yield and base ration intake consequently to concentrate reduction. On average, FLEX cows increased their base ration intake by 0.59 kg DM for each kilogram of concentrate removed. Their milk yield decreased by 0.49 kg per kilogram of concentrate removed, compared with 0.94 kg for FIX cows (Table 4).

Individual variability of responses. Across all measured variables, individual variability was present in both treatments, but consistently higher in the FIX treatment compared to the FLEX treatment (Fig. 4). For instance, the SD of milk yield response was 0.64 kg/d in FIX cows compared to 0.58 in FLEX cows. Similarly, the SD of the base ration intake response was 0.53 and 0.43 kg DM per kilogram of concentrate removed in FIX and FLEX cows, respectively.

The distribution of the FLEX cow-sequences among the nine response profiles further illustrated the diversity of adaptive responses to concentrate reduction (Table 5). Most cow-sequences showed moderate or high compensation through increased base-ration intake (profiles B+ and B++), while milk-yield responses were relatively evenly distributed among the three milk-response categories. Consequently, FLEX cows expressed a wide range of response profiles combining different levels of intake compensation and milk-yield loss.

In contrast, the distribution of the FIX cow-sequences among milk response profiles was less balanced and characterized by a predominance of profiles associated with substantial milk yield losses (Table 5). Only a small proportion of cow-sequences belonged to the profile with the lowest milk-yield reduction (M0).

Profiles stability from one sequence to the following. Table 6 presents the percentage of cows that changed their response profile between two consecutive sequences in both the FLEX and FIX treatments**.**

In the FLEX group, the analysis of combined profiles (B × M) revealed substantial within-cow variation across sequences. Only 25% and 9.5% of cows maintained the same combined response profile between sequences 1 and 2 and between sequences 2 and 3, respectively. Most cows changed profile by one or two classes, indicating limited consistency of the combined response profiles over time. Similar patterns were observed when considering base-ration-intake responses (B) separately. Milk-yield responses (M) were somewhat more stable, with 39.3–52.4% of cows remaining in the same profile across consecutive sequences.

For FIX cows, milk-yield response was the only component evaluated across sequences. Between 40.0 and 45.8% of cows maintained the same milk-response profile across consecutive sequences, while the remaining cows shifted by one or two profile classes (Table 6).

DISCUSSION

This study aimed to characterize the diversity and structure of short-

term responses to concentrate reduction. The results demonstrate that cows with similar production level and parity can exhibit markedly different adaptive responses, supporting the concept of response profiling as a potential phenotyping tool. A particular strength of this study is the combination of direct individual measurements of base-ration intake, repeated concentrate-reduction challenges across lactation, and the comparison between cows with flexible versus restricted access to the base ration. Together, these features provided a unique opportunity to characterize adaptive response diversity under controlled nutritional conditions. It was hypothesized that (1) cows differ in their responses to concentrate reduction, (2) cows with restricted access to a base ration will only compensate for reduced concentrate supply by decreasing their milk production, and (3) the distribution of response profiles would reflect these differences in compensation strategies.

Overall, the results support the existence of substantial inter-individual variability in responses to concentrate reduction and confirm that access to the base ration influences the expression of these responses. However, the observed response profiles should be interpreted as short-term adaptive patterns rather than evidence of stable cow-level phenotypes. In addition, because body-reserve mobilization was not directly incorporated into the response-profile framework, the proposed profiles do not capture all potential adaptive mechanisms involved in the response to concentrate reduction.

While group averages showed that cows with ad libitum access (FLEX treatment) could partially compensate for the reduced concentrate by increasing their base ration intake and mobilizing body reserves, these average figures masked substantial cow-to-cow differences. The diversity of individual response profiles, both in terms of milk yield and base ration intake, demonstrates that cows adopt various strategies to maintain energy balance, and that these strategies may change over time. Even within the same feeding treatment, responses varied not only in direction (increase, decrease, or no change) but also in magnitude, confirming that individual cows react differently to dietary constraints.

Importantly, the distribution of response profiles underlined that only a subset of cows were able to maintain milk yield without increasing intake, or to compensate fully by increasing base ration intake. Conversely, some cows responded with substantial milk yield reductions and little to no intake adjustment. These findings illustrate that response to dietary challenges is not homogeneous. However, their practical relevance for precision feeding depends on the ability to

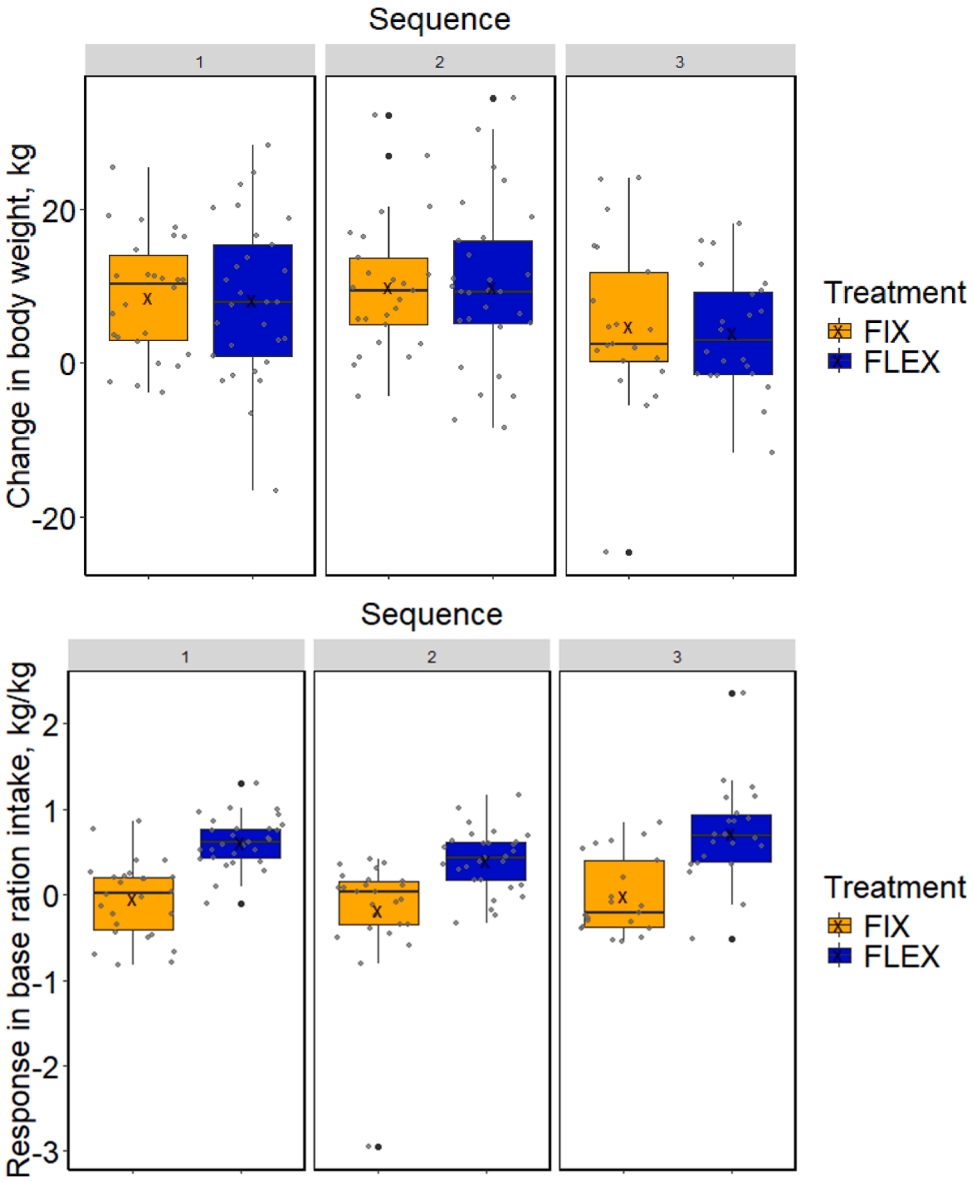


Fig. 4. Response variables according to feeding treatment (FLEX, FIX) and experimental sequence. Grey dots represent individual observations and black crosses indicate group means.

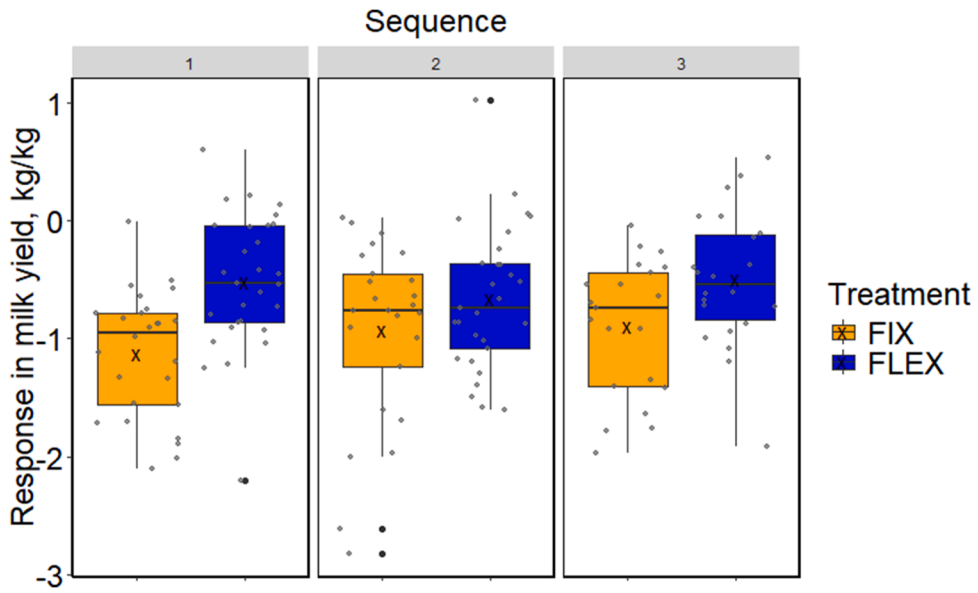


Fig. 4. (*continued*).

Table 5
a. Distribution of cow-sequences (N = 60 × 1-3 sequences) according to treatment (FIX vs. FLEX), base ration intake response (B0: no compensation, B+: moderate compensation, B++: high compensation) and milk yield response (M0: no milk loss, M-: moderate loss, M–: high milk loss) following concentrate reduction. Values correspond to the total number of cow-sequences across the three experimental sequences. **b.** Distribution of cow-sequences according to treatment, response profile, and experimental sequence. Values correspond to the number of cow-sequences classified in each response profile during sequence 1, sequence 2, and sequence 3.

5.a.						
Treatment	FLEX				FIX[1]	
Response	B0	B+	B++	Total	Total	TOTAL
M0	1	14	10	25	9	34
M-	6	16	5	27	25	52
M–	9	15	4	28	38	66
TOTAL	16	45	19	80	72	152

5.b. Treatment	FLEX				FIX[1]	
Response	B0	B+	B++	Total	Total	TOTAL
M0	0 / 1 / 0	6 / 4 / 4	5 / 2 / 3	11 / 7 / 7	1 / 5 / 3	12 / 12 / 10
M-	1 / 4 / 1	7 / 4 / 5	1 / 1 / 3	9 / 9 / 9	7 / 10 / 8	16 / 19 / 17
M–	2 / 5 / 2	6 / 8 / 1	1 / 0 / 3	9 / 13 / 6	18 / 10 / 10	27 / 23 / 16
TOTAL	3 / 10 / 3	19 / 16 / 10	7 / 3 / 9	29 / 29 / 22	26 / 25 / 21	55 / 54 / 43

[1] Cows in the FIX treatment had restricted access to the base ration and therefore could only be classified according to their milk-yield response.

Table 6
Stability of response profiles across consecutive concentrate-reduction challenges. Values correspond to the percentage of cows assigned to each level of profile change between two consecutive sequences. Profile change was calculated as described in the Materials and Methods section. Higher values indicate larger changes in response profile between sequences.

6.a. Transition from sequence 1 to sequence 2.				
Profile Change	FLEX B × M[1] (n = 28)	FLEX B[2] (n = 28)	FLEX M[2] (n = 28)	FIX M[2] (n = 24)
0	25.0	39.3	39.3	45.8
1	21.4	46.4	50.0	37.5
2	39.3	14.3	10.7	16.7
3	10.7	-	-	-
4	3.6	-	-	-

6.b. Transition from sequence 2 to sequence 3				
Profile Change	FLEX B × M[1] (n = 21)	FLEX B[2] (n = 21)	FLEX M[2] (n = 21)	FIX M[2] (n = 20)
0	9.5	19.0	52.4	40.0
1	42.9	66.7	38.1	50.0
2	33.3	14.3	9.5	10.0
3	14.3	-	-	-
4	0.0	-	-	-

[1] B × M = combined response profile based on both base-ration-intake response (B) and milk-yield response (M)
[2] B and M correspond to profile stability evaluated separately for base-ration-intake response and milk-yield response, respectively.

identify which cows belong to each adaptation profile. At present, such profiles can only be determined retrospectively, following a dietary challenge. This limitation highlights the need to identify predictive indicators of individual adaptation capacity if precision feeding strategies are to be implemented proactively, or alternatively to rely on feeding systems that allow cows to self-regulate their intake.

Intake and milk-yield responses to a concentrate reduction. The results showed that dairy cows differed markedly in their adjustments of base-ration intake and milk yield following concentrate reduction. These two response dimensions formed the basis of the response-profile framework developed in this study. In the FLEX group, there was high inter-individual variability in both responses, indicating that these two levers were used to different extents by different cows. This dual adjustment strategy echoes the concept of substitution rate between concentrates and forages (Faverdin et al., 1992), although in the present study substitution occurred between concentrate and a base ration composed primarily of forages (78% of DM). When concentrate supply was reduced, FLEX cows experienced a decrease of approximately −17 MJ NE/d from concentrate, which was partially compensated by an increase in base ration intake providing about +9 MJ NE/d. The remaining energy deficit was mainly expressed as a reduction in milk energy output (−2.7 MJ NE/d), resulting in a moderate deterioration of energy balance. In contrast, cows in the FIX treatment were not allowed to increase base ration intake and therefore experienced a larger reduction in net energy intake (approximately −12 MJ NE/d), which was primarily compensated by a greater reduction in milk energy output

(−6.3 MJ NE/d), leading to a more pronounced negative energy balance. These results confirm that cows in similar lactation stages and with comparable requirements experience a worsened energy balance when substitution is constrained, consistent with previous observations of milk yield decline following concentrate reduction when no compensatory intake occurs (Berg and Ekern, 1993; Friggens et al., 1998). Importantly, individual response profiles revealed that these energy pathways were not tightly coupled: some cows substantially increased base ration intake yet still exhibited marked milk yield losses, whereas others showed limited intake adjustment while maintaining milk production.

High inter-individual variability in milk and intake responses to concentrate reduction. The mechanisms discussed below should be considered as biologically plausible interpretations of the observed response patterns rather than mechanisms directly demonstrated by the present study. One of the key findings of this study is the marked inter-individual variability in responses to concentrate reduction, particularly among FLEX cows. Beyond documenting this variability, an important question is what differentiates cows belonging to the different response profiles. Several, non-mutually exclusive mechanisms may underlie these contrasted adaptive strategies.

Differences in feeding behavior and intake regulation are likely to play a central role. Individual cows may differ in their motivation to increase trough visits, their ability to cope with increased bulk intake, or their sensitivity to rumen fill and satiety signals, which could explain why some cows substantially increased base ration intake (B++), whereas others did not (B0), despite similar access conditions. Such behavioral variability has been previously reported and shown to be consistent over time in dairy cows (Fischer et al., 2018). In addition, cows may differ in digestive capacity, rumen volume, passage rate, and feed efficiency, all of which influence their ability to increase intake and extract energy from fibrous diets following a reduction in concentrate supply (Faverdin et al., 1991; Allen, 2000).

Beyond intake regulation, individual differences in energy partitioning may also contribute substantially to response heterogeneity. Dairy cows differ in the relative priority given to milk production, body reserve mobilization, growth, and restoration of body condition, particularly during early and mid-lactation (Friggens et al., 2004; Wathes et al., 2007). Consequently, cows exposed to a similar energy deficit may respond differently: some may maintain milk yield through greater mobilization of body reserves, whereas others may reduce milk synthesis to preserve body condition and metabolic status. Such differences in metabolic flexibility and endocrine regulation have been associated with variation in nutrient partitioning, resilience to nutritional challenges, and overall production efficiency (Friggens et al., 2013; Wathes et al., 2007). Because body-reserve mobilization was not directly measured in the present study, the contribution of this mechanism remains speculative, but it may partly explain why intake compensation and milk-yield responses were not always tightly coupled.

The thresholds used to define response profiles were intentionally selected to provide simple and interpretable categories rather than to represent discrete biological states. Consequently, the proposed classification should be viewed as an exploratory framework for describing response diversity among cows rather than as evidence for biologically distinct groups. Because no formal sensitivity analysis was conducted, the robustness of this classification to alternative threshold definitions remains to be established. Future studies should therefore assess the consistency of the identified response profiles across different threshold values and production environments.

Together, these observations highlight the need for a better understanding of the biological basis and consequences of the different response profiles. Beyond describing differences in intake and milk-yield responses, future research should determine whether particular profiles are associated with differences in metabolic status, body-reserve mobilization, robustness, resilience to nutritional challenges, health, or welfare outcomes. Such information is essential to establish whether certain response profiles represent more desirable adaptive strategies than others.

Once the biological significance of these profiles is better understood, an important next step will be to identify practical proxies capable of anticipating individual response profiles. Potential indicators include early-lactation intake dynamics, body condition score trajectories, milk component patterns (e.g., fat-to-protein ratio), behavioral traits related to feeding activity, or responses to previous nutritional challenges. Identifying such proxies would be a critical step toward moving from retrospective characterization of response profiles to proactive, individualized feeding strategies.

Average responses confirm a partial substitution effect. The average responses observed in our ad libitum group are consistent with previous studies showing moderate substitution and milk yield reduction in response to concentrate supply changes. On average, for the FLEX cows, the reduction of concentrate intake was only partially compensated by an increase in base ration intake. This response aligns with the substitution mechanism in ruminants (Faverdin et al., 1992), whereby a reduction in dietary energy density, often associated with reduced concentrate levels, leads to an increase in intake of the basal diet to maintain energy supply. However, this compensation remained incomplete in our study, suggesting that, under the conditions of the present study, cows were only able to partially increase intake of the PMR type base ration in response to reduced extra-concentrate supply. Finally, Aguerre et al. (2011) reported that altering the forage-to-concentrate ratio had no significant impact on DMI of cows fed ad libitum but influenced milk composition, increasing fat content while reducing protein concentration. In our study, the responses observed in both FLEX and FIX cows align with these findings, indicating that our cows exhibited expected physiological adaptations to changes in concentrate supply. However, interpretation of milk-composition responses requires caution. In addition to changes in the forage-to-concentrate ratio, the greater energy deficit experienced by some cows, particularly in the FIX treatment, may also have contributed to the observed changes in milk composition. Consequently, the present data do not allow the respective contributions of dietary composition and energy status to be disentangled.

The observed responses should also be interpreted in the context of the nutritional value of the basal ration, which already covered a substantial proportion of cows' nutrient requirements. Consequently, the responses reported here are specific to the feeding conditions of the present experiment and should not necessarily be extrapolated to systems relying on a less nutrient dense basal ration, where responses to concentrate reduction may differ. An additional limitation is that the present study evaluated only a single extra concentrate contrast, from 4 to 1 kg/cow per day. Consequently, the observed intake and milk-yield responses are specific to this nutritional challenge and should not be interpreted as universal marginal responses applicable across other levels of concentrate reduction.

Response profiles to a concentrate reduction are not necessarily consistent over time. Although some cows showed consistent responses to repeated concentrate reductions, we observed substantial changes in others, particularly between sequences 2 and 3, which coincided with a heatwave. Heat stress is known to affect feed intake, milk yield, energy balance, and feeding behavior in dairy cows and may therefore have contributed to the reduced consistency of response profiles observed during the final sequence. Consequently, part of the variability observed between sequences may reflect environmental conditions rather than inherent differences in cows' adaptive strategies. This external factor likely influenced feed intake and milk yield, adding complexity to the interpretation of repeatability. Milk yield responses were more stable over time than trough intake responses, suggesting that cows may prioritize stability in milk yield, possibly through internal regulation of energy partitioning (e.g., body reserve mobilization) (Friggens et al., 2013; Wathes et al., 2007). The repeated concentrate-reduction challenges allowed us to evaluate whether

response profiles remained consistent over time rather than relying on a single challenge event.

This variability raises questions about the stability and predictability of individual response profiles. While metabolic profiling (e.g., Gaillard and Abarnou, 2024) could provide further insight, our results already point toward the need to integrate individual variability and its temporal consistency into feeding management strategies. Repeatability is not absolute, and external factors (e.g., temperature, health, or carry-over effects) and internal factors (change in physiological strategies over time) may limit the ability to predict responses based on previous behavior. Consequently, the response profiles identified in the present study should be interpreted as observed adaptive response patterns rather than definitive evidence of stable individual phenotypes.

Interpretation of BW changes requires particular caution. In dairy cows, short-term fluctuations in BW may reflect not only changes in body reserves but also variation in digestive fill, gut contents, hydration status, and pregnancy-related growth. Consequently, apparent discrepancies between BW trajectories and calculated energy balance may occur over relatively short periods. The relatively large body-weight gains and losses observed in some cows over the three-week experimental phases are unlikely to reflect body-reserve changes alone and probably also include variation associated with digestive fill and hydration status. This limitation may partly explain the apparent discrepancy between the positive body-weight changes and the negative calculated energy balances observed during the experimental periods. This limitation reinforces the need for complementary indicators, such as body condition score dynamics, body composition measurements, or metabolic biomarkers, when investigating the role of body reserve mobilization in adaptive responses to nutritional challenges.

Several limitations should also be considered when interpreting profile consistency. First, the repeated-sequence design did not include a wash-out period independent of the subsequent C4 phase. Consequently, the C4 phases simultaneously served as recovery periods from the previous challenge and as baseline periods for the subsequent challenge. Although sequence was included in all statistical models and cows were re-exposed to a common feeding condition before each challenge, carry-over effects related to body reserve dynamics, feeding behavior adaptation, or previous nutritional history cannot be completely excluded. Second, several cow-sequences were excluded due primarily to health disorders affecting concentrate intake. Although these exclusions were necessary to ensure that calculated responses reflected the experimental treatments rather than disease-related effects, they may have introduced some degree of selection bias, as cows experiencing health problems could differ in their adaptive capacity, feeding behavior, or production responses compared with the retained population. In addition, all six cows that were completely excluded from the study belonged to the FIX treatment. Although the available data do not allow us to determine whether this distribution was directly related to the feeding treatment, a potential association between restricted access to the base ration, health status, and adaptive responses cannot be completely excluded. The present analyses were designed to characterize observed response heterogeneity rather than to estimate individual response parameters. Future studies could use random-slope or variance-component approaches to better distinguish between-cow differences in adaptive responses from within-cow temporal variability and thereby quantify the relative contributions of stable and transient sources of variation.

Implications for feeding strategies and future directions. The marked variability in cows' responses to reduced concentrate supply highlights the limitations of uniform feeding strategies based solely on lactation stage or average production. Some cows were able to compensate for reduced concentrate supply through increased base ration intake, whereas others exhibited larger milk yield losses, indicating that a single feeding rule is unlikely to be optimal for all individuals. Characterizing cows with differing substitution capacities provides a useful framework for understanding adaptive diversity among cows and may ultimately contribute to the development of more individualized feeding approaches.

The comparison between FLEX and FIX cows made it possible to isolate the role of intake flexibility in shaping adaptive responses to concentrate reduction and to demonstrate its importance for limiting milk-yield losses.

A major challenge remains the identification of response profiles a priori. In the absence of reliable predictors, individual responses currently need to be identified retrospectively following a dietary challenge. Future research should investigate whether early-lactation intake patterns, body condition dynamics, milk component trajectories, behavioral indicators, parity, lactation stage, baseline production level or body condition can help predict individual adaptive responses to nutritional challenges. If reliable predictors can be identified, integrating such indicators into automated decision-support tools may facilitate the future development of response-based feeding strategies.

The response profiles proposed here were based on predefined thresholds selected for their biological interpretability and practical relevance. Alternative data-driven approaches, such as clustering methods, latent class analysis, or random-slope-based classifications, could provide complementary insights into response heterogeneity and may help refine response profiling in future studies.

Beyond intake and milk yield, mobilization of body reserves likely represents an additional mechanism by which cows adapt to reduced energy supply. Importantly, cows maintaining milk yield following concentrate reduction may achieve this response through different biological pathways. Some may increase base-ration intake, whereas others may rely more heavily on body-reserve mobilization. The relative contribution of these mechanisms may also be influenced by differences in endocrine regulation, including the somatotropic axis, and by cows' genetic potential for milk production, both of which affect nutrient partitioning and adaptive responses to nutritional challenges (Wathes et al., 2007; Friggens et al., 2013). Consequently, a limited milk-yield response should not necessarily be interpreted as a more desirable adaptive strategy if it is achieved at the expense of excessive mobilization of body reserves. However, body reserve mobilization was not directly measured in the present study and therefore remains a plausible interpretation rather than a demonstrated mechanism. Future work should better quantify its contribution using indicators such as body condition score, energy balance estimates, or blood metabolites. Future studies combining intake measurements, production data, body condition dynamics, and metabolic indicators would provide a more complete characterization of the biological mechanisms underlying individual responses to concentrate reduction. In addition, emerging sensor-based phenotyping technologies may provide useful tools for predicting individual response profiles. Automated monitoring systems based on 3D imaging, body weight recording, feeding behavior sensors, thermography, or other precision livestock farming technologies could help identify cows differing in their capacity to adjust intake, mobilize body reserves, or maintain milk production following nutritional challenges. Although such technologies were not evaluated in the present study, they may contribute to the future development of predictive indicators allowing response profiles to be identified before dietary interventions are implemented.

Milk yield responses were evaluated using raw milk yield rather than net energy in milk. While energy-corrected indicators would provide a more physiologically accurate assessment under energy-limiting conditions, gross milk yield remains more readily available and interpretable in commercial settings. This choice aligns with the objective of developing approaches that rely on simple, field-relevant indicators, although increasing availability of sensor-based phenotyping may enable more detailed assessments in the future. Future work should evaluate whether the response profiles identified here remain consistent when production responses are expressed using energy-corrected milk, fat- and protein-corrected milk, or other energetically adjusted production indicators.

Although further validation is required, the response-profile framework provides a useful descriptive approach for characterizing adaptive diversity among cows and may serve as a basis for future phenotyping studies.

Finally, the substantial within-cow variability in response profiles observed across experimental sequences indicates that response consistency was only partial. The stability of these profiles across longer periods, different lactation stages, and varying environmental conditions remains to be established. Further work is therefore required to validate these profiles, identify reliable predictors, and determine whether they can ultimately support individualized feeding approaches under commercial conditions.

Conclusion

This study demonstrates that short-term responses of dairy cows to a reduction in concentrate supply are highly variable and structured, even among cows with similar production level and parity. While substitution between concentrate and base ration is a well-known phenomenon, our results show that this substitution capacity differs markedly among individuals. This diversity can be described using predefined response profiles combining changes in base ration intake and milk yield. Importantly, restricting access to the base ration constrained the expression of these compensatory strategies and systematically increased milk yield losses, indicating that ad libitum access to the base ration is important for cows to fully express their intake-compensation responses to concentrate reduction. Beyond confirming average substitution effects, this work highlights that cows rely on different combinations of intake- and production-driven responses to cope with a nutritional challenge. The proposed response profiles should therefore be viewed as an initial phenotyping framework for characterizing diversity in intake and milk-yield responses rather than as stable cow-level phenotypes. Because body-reserve mobilization was not directly incorporated into the response-profile framework, the present classification does not capture all potential adaptive pathways involved in the response to concentrate reduction. Future research should focus on identifying predictive indicators, validating response profiles across time and environments, and determining whether such profiles can ultimately support individualized feeding approaches under commercial conditions.

Declaration of AI and AI-assited technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT to correct language errors and to shorten selected sections for clarity and conciseness. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

C. Gaillard: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **L. Brun-Lafleur:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **N. Dermenjian:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Y. Huang:** Writing – review & editing, Visualization, Validation. **L. Delaby:** Writing – review & editing, Visualization, Validation, Conceptualization. **R. Lehuraux:** Visualization, Investigation, Formal analysis, Data curation. **J. Jurquet:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Oble:** Resources, Methodology. **A. Fischer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., Broderick, G.A., Arndt, C., 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. J. Dairy Sci. 94, 3081–3093. https://doi.org/10.3168/jds.2010-4011.

Allain, C., Quinton, P., Philibert, A., Cros, P., Herman, M., Cimino, M., Frappat, B., Larsonneur, S., Lafont, N., 2015. La connectivité des élevages laitiers. Renc. Rech. Rum., 22, 403.

Allen, M.S., 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. 83, 1598–1624. https://doi.org/10.3168/jds.S0022-0302(00)75030-2.

André, G., Berentsen, P.B.M., Van Duinkerken, G., Engel, A.G.J.M., Oude Lansink, R., 2010. Economic potential of individual variation in milk yield response to concentrate intake of dairy cows. J. Agric. Sci. 148, 263–276. https://doi.org/10.1017/S0021859610000134.

André, G., Bleumer, E.J.B., Van Duinkerken, G., 2009. Evaluation of an application for dynamic feeding of dairy cows. Precision Livestock Farming 2009. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 25–32.

Bazin, J., Dupont, J., Martin, P., 1984. RNED bovin, Institut technique de l'élevage bovin, Paris, France.

Berg, J., Ekern, A., 1993. Long-term effects of concentrate level in dairy cows. Acta Agric. Scand. Sect. A Anim. Sci. 43, 35–43.

Faverdin, P., Dulphy, J.P., Coulon, J.B., Garel, J.P., Rouel, J., Marquis, B., 1991. Substitution of roughage by concentrates for dairy cows. Livest. Prod. Sci. 27, 137–156. https://doi.org/10.1016/0301-6226(91)90092-5.

Faverdin, P., Dulphy, J.P., Coulon, J.B., Vérité, R., Garel, J.P., Rouel, J., Marquis, B., 1992. Les phénomènes de substitution fourrages-concentrés chez la vache laitière. INRAE Prod. Anim. 5, 127–135. https://doi.org/10.20870/productions-animales.1992.5.2.4227.

Fischer, A., Friggens, N.C., Berry, D.P., Faverdin, P., 2018. Isolating the cow-specific part of residual energy intake in lactating dairy cows using random regressions. Anim 12, 1396–1405. https://doi.org/10.1017/s1751731117003214.

Friggens, N.C., Emmans, G.C., Kyriazakis, I., Oldham, J.D., Lewis, M., 1998. Feed intake relative to stage of lactation for dairy cows consuming total mixed diets with a high or low ratio of concentrate to forage. J. Dairy Sci. 81, 2228–2239. https://doi.org/10.3168/jds.S0022-0302(98)75802-3.

Friggens, N.C., Ingvartsen, K.L., Emmans, G.C., 2004. Prediction of body lipid change in pregnancy and lactation. J. Dairy Sci. 87, 988–1000. https://doi.org/10.3168/jds.S0022-0302(04)73244-0.

Friggens, N.C., Brun-Lafleur, L., Faverdin, P., Sauvant, D., Martin, O., 2013. Advances in predicting nutrient partitioning in the dairy cow: recognizing the central role of genotype and its expression through time. Animal 7, 89–101.

Gaillard, C., Abarnou, J., 2024. Responses of dairy cows to weekly individualized feeding strategies regarding their metabolic status. J. Dairy Sci. 107, 10776–10786. https://doi.org/10.3168/jds.2024-25209.

INRA, 2018. In: Nozière, P., Sauvant, D., Delaby, L. (Eds.), Alimentation des ruminants. Editions Quae, Versailles, France, p. 728 pages.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest Package: Tests in linear mixed effects models. J. Stat. Softw. 82, 1–26. https://doi.org/10.18637/jss.v082.i13.

Nicolas, E., Allain, C., Baron, A., 2024. Digitalisation des élevages: résultats d'une enquête sur les équipements numériques des éleveurs de ruminants en France. SPACE.

Pardue, F.E., Fosgate, O.T., O'Dell, G.D., Brannon, C.C., 1975. Effects of complete ensiled ration on milk production, milk composition, and rumen environment of dairy cattle. J. Dairy Sci. 58, 901–906. https://doi.org/10.3168/jds.S0022-0302(75)84655-8.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Wathes, D.C., Cheng, Z., Bourne, N., Taylor, V.J., Coffey, M.P., Brotherstone, S., 2007. Differences between primiparous and multiparous dairy cows in the inter-relationships between metabolic traits, milk yield and body condition score in the periparturient period. Domest. Anim. Endocrinol. 33, 203–225. https://doi.org/10.1016/j.domaniend.2006.05.004.

Van Soest, P.J., 1967. Development of a comprehensive system of feed analyses and its application to forages. J. Anim. Sci. 26, 119–128. https://doi.org/10.2527/jas1967.261119x.

Yan, T., Patterson, D.C., Gordon, F.J., 1998. The effect of two methods of feeding the concentrate supplement to dairy cows of high genetic merit. Anim. Sci. 67, 395–403. https://doi.org/10.1017/S1357729800032793.