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Yield gap analysis of feed-crop livestock systems: The case of grass-based beef production in France

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A B S T R A C T

Sustainable intensification is a strategy contributing to global food security. The scope for sustainable intensification in crop sciences can be assessed through yield gap analysis, using crop growth models based on concepts of production ecology. Recently, an analogous cattle production model named LiGAPS-Beef (Livestock simulator for Generic analysis of Animal Production Systems – Beef cattle) was developed, which allows yield gap analysis in beef production systems. This paper is the first to assess yield gaps of integrated feed-crop livestock systems, to analyse underlying causes of yield gaps, and to identify feasible improvement options. We used grass-based beef production in the Charolais area of France as a case study. To this end, we combined LiGAPS-Beef with crop growth models that simulate grass production (fresh grass under grazing, grass silage, hay) and wheat production (concentrate). Feed crop and cattle production were integrated to simulate potential and resource-limited live weight (LW) production per hectare. Potential production is defined as the theoretical maximum LW production per ha, in the absence of resource or management limitations. Resource-limited production is determined by availability of one or several resources: water and nutrients for crops, and feed quality and quantity for animals. Potential production of a cattle herd with an *ad libitum* diet of grass silage was 2380 kg LW ha^{-1} $year^{-1}$ and resource-limited production was 664 kg LW ha^{-1} $year^{-1}$. Actual LW production (354 kg LW ha^{-1} $year^{-1}$) was 15% of the potential production, implying a relative yield gap of 85%, and 53% of the resource-limited production, implying a relative yield gap of 47%. Applying yield gap analysis disentangled the major biophysical causes of these yield gaps: feeding diets other than the *ad libitum* grass silage diet, water-limitation in feed crops, and sub-optimal management. These yield gaps suggest scope to intensify beef production. We demonstrate, however, that yield gap mitigation decreased the operational profit per kg LW under the European regulations for bovine and grassland premiums operational in 2014. Hence, as expected, the premiums aiming to support farmers' income and to promote sustainable agriculture and rural development were not conducive to narrow yield gaps at the same time. The current common agricultural policy (CAP, 2015–2020) provides more scope for intensification, such as increasing stocking density *via* better grassland management.

1. Introduction

Sustainable intensification is a proposed strategy to increase food production on existing farmland, while reducing negative impacts of agriculture on the environment (Garnett et al., 2013). The scope for intensification in agriculture can be assessed by mechanistic models based on concepts of production ecology (Evans and Fischer, 1999; Van der Linden et al., 2015; Van Ittersum and Rabbinge, 1997). These biophysical models simulate potential (*i.e.* theoretical maximum) and resource-limited production under ideal management conditions, and can be used to identify the major biophysical constraints for production. The difference between potential or resource-limited production and actual production achieved on farms is defined as the so-called yield gap, which indicates the biophysical scope to intensify production on a given area (Lobell et al., 2009; Van Ittersum et al., 2013). Yield gaps exist for a variety of reasons, including farm endowment, farmer

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objectives, and economic and policy factors (De Koeijer et al., 1999; Van Dijk et al., 2017).

Mechanistic models can also be used to identify constraining biophysical factors for crop growth, which is a crucial step in yield gap analysis. Insights from yield gap analyses contribute to the exploration of improvement options that increase production and mitigate yield gaps. Such improvement options can (and must) then also be assessed from an economic and social perspective. Yield gap analysis has been applied numerous times in crop production systems with local to more global approaches (Van Ittersum et al., 2013). Assessing yield gaps of crops with mechanistic models is widely established in crop sciences (Bouman et al., 1996b; Jones et al., 2003; Keating et al., 2003).

Although concepts of production ecology were initially applied in crop sciences only, they have recently been extended to the livestock sciences (Van de Ven et al., 2003; Van der Linden et al., 2015). This led to the development of LiGAPS-Beef (Livestock simulator for Generic analysis of Animal Production Systems – Beef cattle), a mechanistic model simulating potential and feed-limited growth of beef cattle. This model can also be used to identify constraining factors for beef production (Van der Linden, 2017). Model evaluation showed that live weight (LW) gain was simulated reasonably to good (Van der Linden, 2017). LiGAPS-Beef seems an adequate tool to analyse yield gaps in beef production systems. We note that livestock production is dependent on feed production, which has to be taken into account when assessing the scope to increase livestock production per hectare of farmland. The aim of this paper is, therefore, to quantify yield gaps of the integrated feed-crop livestock production systems, to analyse their yield gaps, and to explore improvement options. We used grass-based beef production in the Charolais area of France as a case study.

The Charolais area is the northern part of the Massif Central, which is a major region for beef production in France where 35% of the national suckler-cow herd is kept (Veysset et al., 2014b). The main beef breed used in France is the Charolais breed, which accounts for 1.5 million suckler cows out of the total of 4.1 million. In France, 41% of the Charolais cows is kept in the Charolais area (Veysset et al., 2015). The Charolais area was selected as a case for yield gap analysis because of its important contribution to beef production in France, good data availability, and assumed scope to increase farm profitability *via* yield gap mitigation. Beef production systems in the Charolais area are dependent on coupled and decoupled premiums (*i.e.* respectively premiums linked to and independent of cattle production) from the European Union's common agricultural policy (CAP). The value of premiums received by farmers is larger than their net income from agriculture (Veysset et al., 2005; Veysset et al., 2014c).

2. Materials and methods

2.1. General approach

Yield gaps for beef production systems in the Charolais area were quantified from the perspective of a feed-crop livestock system, assuming that all feed is produced in the area. The feed-crop livestock system includes beef cattle and the land area to produce all the feed consumed by these cattle, irrespective whether it was produced on-farm or off-farm. Cattle production was expressed as feed efficiency (FE), in kg LW per ton dry matter (DM), whereas crop production was expressed as annual yield, in ton DM per hectare per year. Multiplication of cattle and crop production results in kg LW produced per hectare per year (Van der Linden et al., 2015).

All feed was assumed to be produced in the Charolais area of France. Concentrates fed to cattle were represented by wheat. Grasslands were assumed to consist of perennial ryegrass (*Lolium perenne* L.) only. Yield gaps in feed-crop livestock systems were defined as the difference between potential (or resource-limited) LW production and actual LW production per hectare (Van der Linden et al., 2015). Potential crop production is determined by the genotype of the crop species, and the climate. Limited crop production is determined by water and nutrient supply, in addition to the genotype and climate. Farm management is assumed ideal under both potential and limited crop production (Van Ittersum and Rabbinge, 1997). Potential production is the most relevant benchmark for irrigated crop production, and water-limited production for rainfed crop production (Van Ittersum et al., 2013). In analogy, potential livestock production is determined by the genotype of the livestock species, and the climate. Limited livestock production is determined by feed quality and the quantity of available feed. Farm management is ideal under potential and limited livestock production (Van de Ven et al., 2003; Van der Linden et al., 2015).

Potential, resource-limited, and actual production were assessed for both feed crops and cattle. Actual production in the Charolais area was calculated from literature (Réseaux d'Élevage Charolais, 2014; Veysset et al., 2005; Veysset et al., 2014b). Potential and feed-limited production of beef cattle were simulated with the model LiGAPS-Beef (Van der Linden, 2017). Potential and water-limited production of fresh grass, hay, and grass silage were simulated with the model LINGRA (Light INterception and utilization-GRAss) (Schapendonk et al., 1998). Potential and water-limited production of wheat were simulated with the model LINTUL-2 (Light INTerception and UtiLization) (Van Ittersum et al., 2003). Potential and water-limited production of silage maize were derived from literature (De Koning and van Diepen, 1992). LiGAPS-Beef was combined with LINGRA, accounting for the interactions between cattle and grass. Next, yield gaps were quantified, and their biophysical causes were identified based on the simulation results of LiGAPS-Beef and the crop growth models. Subsequently, improvement options for yield gap mitigation were explored.

2.2. Actual production

Actual production was calculated for 12 farm types with Charolais cattle (Réseaux d'Élevage Charolais, 2014). A farm type represents a typical farming system among the diversity of systems in the Charolais area and reflects the consistent functioning of this system. Data for the farm types are multiple-year averages, and were derived from observations (farm networks) and expert knowledge. Eight out of the twelve farm types were cow-calf systems, in which calves are sold to fattener systems. Four farm types were cow-calf-fattener systems that produced calves (678–718 kg LW) for slaughter (Table 1). The peak in calving ranged from late December to late March. Cattle grazed from spring to autumn, and were housed during winter. The yield of wheat fed to cattle on-farm could not be determined precisely, since farms also imported cereals. We assumed that the average wheat yield was 5.0 t DM ha^{-1} $year^{-1}$ for farm types specialised in beef production, and 5.6 t DM ha^{-1} $year^{-1}$ for farm types focusing on beef *and* cereal crops based on farm surveys conducted among beef farmers in the Charolais area in 2010 and 2011 (Veysset et al., 2014b). Grass intake on permanent grassland was on average 4.8 t DM ha^{-1} $year^{-1}$, and grass intake from grazing after hay production was on average 1.9 t DM ha^{-1} $year^{-1}$ (Veysset et al., 2005). Grass intake was assumed to be equal for all farm types, since it was not specified per farm type in Réseaux d'Élevage Charolais (2014). The average production of maize (10.0–10.5 t DM ha^{-1} $year^{-1}$) and hay (3.2–5.7 t DM ha^{-1} $year^{-1}$) in the farm types were from Réseaux d'Élevage Charolais (2014). Wheat, maize, hay, and grass production per hectare were multiplied with their respective area to calculate the total feed intake of the cattle herd per year. We assumed that feed stocks (hay, wheat, and maize) do not decrease or accumulate over the years to ascertain that feed consumption is on average equal to on-farm feed production plus feed import from within the region. If feed stocks would decrease or accumulate, the beef production per hectare per year would be overestimated or underestimated. The percentage of wheat in the diets varied between farm types, from 4.8% to 17.0%. Three farm types cultivated maize on-farm. Maize supplementation accounted for 8.3% to 10.4% of the diet in these farm types. Green maize (grain content