Intensification of cow-calf production: How does the system respond biologically to energy inputs in a long-term horizon?

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ABSTRACT

In southern Brazil, beef cattle production systems generally rely on grazing on natural pastures. However, their forage production, and consequently metabolizable energy (ME) production, is seasonal and influenced by climatic events. Thus, there is a scientific and commercial interest in evaluating and understanding the biological impacts of intensification using pasture irrigation and the effects of El Niño-Southern Oscillation (ENSO) phenomena on the long term on the productivity of cow-calf systems. Therefore, our objective was to develop a simulation model to evaluate the effects of intensification levels, using cultivated pastures and irrigation, on the productivity and on the efficiency metabolizable energy utilization of beef cow-calf systems in a 10-year horizon. This period allows capturing the effects of several production cycles as influenced by ENSO events. The model includes three submodels: herd structure, herd ME requirements, and forage ME production. The results of the present study demonstrate that the proposed model is able to evaluate the influence of intensification of grazing systems on metabolizable energy production, carrying capacity, productivity and biological efficiency of beef cow-calf systems over a long-term horizon. Productivity was increased in 15.9% when 20% of the grazing area was intensified and irrigated compared with the modeled non-intensified system, independently of climatic events. The main productive response was the increase in the number of dams in the herd, especially as a result of the use of irrigation. This study proposes different alternatives for increasing the productivity of beef cow-calf systems in southern Brazil.

1. Introduction

The cow-calf phase is the foundation of the entire beef cattle production cycle. However, it is the phase with the lowest biological efficiency (Nasca et al., 2015) due to the presence of few animal classes and its high energy maintenance cost (National Academies of Sciences and Medicine, 2016). It strongly depends on process technologies, because inputs have limited impact on its overall productivity. Nevertheless, the increasing competition for land use (Oliveira et al., 2017) with more profitable activities, such as cash crops, in many regions of the world, have forced cow-calf producers to intensify their production processes.

Energy intake is one of the main factors that influence the productivity of animal production systems, and estimates of energy availability in feedstuffs are essential to describe the nutritional requirements of beef cattle (Galyean et al., 2016). The overall energy requirements of a cow-calf herd include the requirements of cows, replacement heifers, calves before weaning and bulls (Ferrell and Jenkins, 1985). Adequate energy supply is required for maintenance, growth, gestation and lactation in order to ensure the desired output levels (Walsmey et al., 2016). In beef cow-calf systems, approximately 70 to 75% of the total annual metabolizable energy (ME) is used for maintenance functions (Ferrell and Jenkins, 1985).

In southern Brazil, beef cattle production systems generally rely on grazing on natural pastures. However, their forage production, and consequently ME production, is seasonal (Carvalho et al., 2006) and influenced by climatic events. This seasonality is characterized by forage abundance during spring and summer, and forage limitation...
during autumn and winter, resulting in a mismatch between forage production and animal requirements (Carvalho et al., 1998). As consequence of the insufficient forage production during the winter, cattle lose weight, which explains the low productivity of cow-calf systems in that region (Modernel et al., 2018). In order to maintain the stability forage ME production throughout the year in this region, planting forage varieties with high growth potential, such as sudangrass (Sorghum bicolor (L.) Moench x Sorghum sudanense (Piper) Stapf) and pasture irrigation have been proposed (Cosentino et al., 2012; Cotton et al., 2013; Jahanazd et al., 2013). Irrigation may also aid mitigate the effects of climate phenomena, such as El Niño-Southern Oscillation (ENSO), on pasture production. However, experiments to evaluate the use of irrigation in cow-calf systems are expensive, long, and very complex (Diaz-Solis et al., 2006), and therefore, the use of simulation models has shown to be effective for the analysis of the many factors that influence cow-calf systems and their interactions (Jones et al., 2016).

There is a scientific and commercial interest in evaluating and understanding the biological impacts of intensification (Ash et al., 2015) using pasture irrigation and the effects of ENSO phenomena on the long term on the productivity of cow-calf systems. However, in Brazil, especially in the South, there is limited information on this subject. Therefore, our objective was to develop a simulation model to evaluate the biological effects of intensification, using cultivated pastures and irrigation, on the productivity and on the efficiency metabolizable energy utilization of beef cow-calf systems in a 10-year horizon.

2. Materials and methods

2.1. Model overview

The model developed is representative of cow-calf production systems of southern Brazil (Figs. 1 and 2). In this region, the beef herd mainly consists of British breeds (Hereford and Angus) and their crosses with Bos indicus (Braford and Brangus). The climate of this region is humid subtropical (Alvarezes et al., 2013), with an average annual rainfall of 1440 mm. However, rainfall is not evenly distributed throughout the year. During the summer, evapotranspiration is high and often greater than precipitation, resulting in negative water balance and consequently affecting forage production (Berlato and Fontana, 2003; Gelcer et al., 2013).

The model includes three submodels: herd structure, herd ME requirements, and pasture growth were calculated on a daily basis. The baseline production system was defined as 100% natural pasture (Fig. 3). These submodels are linked by information flows, inventories, converters, and connectors. The model may arbitrate initial integer and non-integer values. The non-integer output values are solved by truncation, generating integer values, such as in the case of the number of animals in herd class.

The baseline production system was defined as 100% natural pastures. The model evaluated the intensification of the baseline system by increasing areas of sudangrass (Sorghum bicolor (L.) Moench x Sorghum sudanense (Piper) Stapf) irrigated or not in summer and planted with ryegrass (Lolium multiflorum Lam) and oat (Avena strigosa Schreb) in the winter and not irrigated (Fig. 4). The model evaluates the effect of intensification level over a 10-year period, herein referred as a 10-year horizon. This period allows capturing the effects of several production cycles as influenced by ENSO events.

2.2. The el niño-southern oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) is the most prominent mode of interannual climate variability on Earth (McPhaden et al., 2006). It is generated through coupled interactions between the ocean and atmosphere in the tropical Pacific (Bjerknes, 1969) and alternates between anomalously warm (El Niño) and cold (La Niña) sea surface temperature (SST) conditions. ENSO exerts its impacts on remote regions of the globe through atmospheric teleconnections, affecting extreme weather events worldwide. However, these teleconnections are inherently nonlinear and sensitive to ENSO SST anomaly patterns and amplitudes (Yeh et al., 2018).

Although ENSO is a complex and irregular phenomenon due to nonlinear chaotic dynamics of the ocean-atmosphere system or from stochastic forcing by weather noise (Okumura and Deser, 2010; Tedeschi et al., 2013), ENSO is the most predictable climate fluctuation on the planet. Its predictability is based on wind-driven seasonal variations in the amount of heat stored in the upper few hundred meters of the tropical Pacific Ocean (McPhaden et al., 2006).

In southern Brazil La Niña is related to drought while El Niño is associated with higher water availability (Fontana and Berlato, 1997; Grimm et al., 1998; Marengo and Oliveira, 1998; Fedorova and Carvalho, 2000; Berlato and Fontana, 2003; Gelcer et al., 2013). Thus, in order to operationalize the model within a practical and applied approach in cow-calf production systems, it was arbitrated that the rainfall was considered higher, lower or equivalent to the climatological average, during El Niño, La Niña and Neutral years, respectively (Gelcer et al., 2013).

The identification of the ENSO events, El Niño, La Niña and Neutral years, was based on the National Oceanic and Atmospheric Administration (NOAA) classification, which considers the deviation of ± 0.5 °C in mean sea surface temperature for the identification of the season trimesters (NOAA, 2014; C.H. Pereira et al., 2018). Each climatic event identified was associated with the monthly amount of dry matter produced by the evaluated pastures in order to represent what can occur in a biological system.

2.3. Intensification level

The total area of the production system was set as 1000 hectares (ha) because it is representative of cow-calf systems in the studied region. In order to evaluate the effects of intensification, different scenarios representing intensification levels were simulated. Intensification level was defined as the proportion of the total area that were planted with cultivated pastures during summer and the winter, and to the use of irrigation (only during the summer). The model defined the proportions of the intensified area both during the summer and the winter at each intensification level as equal. Therefore, intensification levels were defined as 0, 5, 10, 15 and 20%, which corresponded to 1000 ha of natural pastures with no intensification (0% intensified), 950 ha of natural pastures and 50 ha intensified (5% intensified), 900 ha of natural pastures and 100 ha intensified (10% intensified), 850 ha of natural pastures and 150 ha intensified (15% intensified), and 800 ha of natural pastures and 200 ha intensified (20% intensified), respectively (Fig. 4). These intensification levels, which may seem low, were chosen because farmers in southern Brazil demonstrate a conservative profile in the process of adopting technologies (M.D. Dill et al., 2015a).

2.4. Herd structure submodel

The herd structure was modeled based on reproductive and survival parameters that are associated with the management practices commonly applied in cow-calf systems in southern Brazil (Table 1). The values of these parameters were kept constant among intensification levels and ENSO events, i.e., the herd structure submodel did not...
consider any individual performance changes among the evaluated scenarios. Therefore, the variation among intensification levels is determined by pasture carrying capacity allowed by the amount of ME produced at each intensification level (Ruviaro et al., 2015). This assumption is accepted when ME offer allows reaching the desired productive, reproductive, and survival performance parameter values.

This submodel includes all animal classes of the herd (Fig. 3). Some assumptions were defined for the submodel evolution, and included average heifer age at first mating as 27 months and average cow stayability of 8 years. In addition, breeding by natural mating was established to occur in December, calving in mid-October and pregnancy diagnosis and weaning in April, on average. The model was set to account for cow surplus in April, at the time of pregnancy diagnosis and weaning. Heifer surplus was accounted for in December, when replacement heifers were selected for breeding, and in April, at the time of pregnancy diagnosis.

The herd structure model was based on animal classes according to number of cows each intensification level is able to carry, associated to the herd parameters (Table 1). Carrying capacities of 231, 278 and 327 dams were calculated for the no-intervention scenario (0% intensified) during La Niña, Neutral and El Niño years, respectively. Based on these scenarios, interventions in energy output were modeled, determining the carrying capacity as a function of intensification level and herd ME requirements.
Fig. 3. Simplified general diagram of the proposed conceptual model for the intensification of beef cow-calf systems. Where A shows the relations among the herd structure submodel variables and B the relations among the energy production submodel variables.

Fig. 4. Simplified general diagram of the setting of intensification levels (intervention). The intensified area consisted of the use of a sudangrass pasture during the summer (January to April) and an oat ryegrass pasture during the winter (June to November).
2.5. Energy requirements submodel

This submodel was adapted from Freer et al. (2012), and allows calculating the amount of ME (Mcal/day) required by a specific animal class fed a specific diet to achieve specific growth, gestation, and lactation targets, or all of these physiological steps together, according to physiological status, as recommended by the CSIRO (2007).

Heifer growth and cow body weight evolution during their productive lives were modeled as recommended by Rovira (1996), aiming to achieve adequate reproductive indicators (Table 1) according to the dynamic parameters of the physiological status of each animal class (Table 2). These input parameters, together with weanling body weight, body weight of surplus cows and heifers, and forage ME content, allow the determination of the energy requirements of each animal at any time point of its productive life. This was the main adaptation of this submodel, which made it more dynamic and functional for the proposed evaluation. The parameter values of the energy requirements submodel (Table 2) were defined as constant among intensification levels and ENSO events.

Table 1
Parameters of the herd structure submodel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/description</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stayability</td>
<td></td>
<td>Years</td>
<td>Bertazzo et al. (2004)</td>
</tr>
<tr>
<td>Age at first mating of heifers</td>
<td></td>
<td>Months</td>
<td>M.D. Dill et al. (2015b)</td>
</tr>
<tr>
<td>Pregnancy risk of nulliparous dams (heifers)</td>
<td></td>
<td>%</td>
<td>Vieira et al. (2006)</td>
</tr>
<tr>
<td>Pregnancy risk of primiparous cows</td>
<td></td>
<td>%</td>
<td>Ciccioli et al. (2003)</td>
</tr>
<tr>
<td>Pregnancy risk of multiparous cows</td>
<td></td>
<td>%</td>
<td>Santos et al. (2004)</td>
</tr>
<tr>
<td>Probability of survival from birth to weaning</td>
<td></td>
<td>%</td>
<td>M.D. Dill et al. (2015b)</td>
</tr>
<tr>
<td>Probability of survival from weaning to one year of age</td>
<td></td>
<td>%</td>
<td>Mazzetto et al. (2015)</td>
</tr>
<tr>
<td>Probability of survival of 1-yr-old heifers</td>
<td></td>
<td>%</td>
<td>Potter et al. (1998)</td>
</tr>
<tr>
<td>Probability of survival of primiparous cows</td>
<td></td>
<td>%</td>
<td>Mazzetto et al. (2015)</td>
</tr>
<tr>
<td>Annual probability of survival of 2nd-calf, multiparous, and last-calf cows</td>
<td></td>
<td>%</td>
<td>Mazzetto et al. (2015)</td>
</tr>
<tr>
<td>Sire to cow ratio</td>
<td></td>
<td></td>
<td>Menegassi et al. (2011)</td>
</tr>
<tr>
<td>Calf weaning live weight</td>
<td></td>
<td>kg</td>
<td>M.D. Dill et al. (2015b)</td>
</tr>
<tr>
<td>Calf current live weight</td>
<td></td>
<td>kg</td>
<td>Potter et al. (1998)</td>
</tr>
<tr>
<td>Calf mature body weight</td>
<td></td>
<td>kg</td>
<td>Cardoso et al. (2016)</td>
</tr>
<tr>
<td>Calf birth weight</td>
<td></td>
<td>kg</td>
<td>Freer et al. (2012)</td>
</tr>
<tr>
<td>Calf weight gain</td>
<td></td>
<td>g/d</td>
<td>Freer et al. (2012)</td>
</tr>
<tr>
<td>Lactation phase</td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>Stage of pregnancy</td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>Calf birth weight</td>
<td></td>
<td>kg</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Calf mature body weight</td>
<td></td>
<td>kg</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Calf weight gain</td>
<td></td>
<td>g/d</td>
<td>Cardoso et al. (2016)</td>
</tr>
<tr>
<td>Proportion of calf ME requirements supplied by the dam's milk</td>
<td></td>
<td>%</td>
<td>Freer et al. (2012)</td>
</tr>
<tr>
<td>Increased cow ME maintenance requirem</td>
<td></td>
<td>%</td>
<td>Freer et al. (2012)</td>
</tr>
</tbody>
</table>

1 Month when heifer surplus after dam replacement in the herd is determined.
2 Month when heifer surplus after pregnancy diagnosis is determined.

2.6. Energy production submodel

The ME production was used to calculate the carrying capacity of each intensification level. ME production is given by the relation among the variables total digestible nutrients (TDN), forage mass and daily dry matter accumulation rate (Fig. 3). However, variables such as pasture type, month of the year and climatic event, which may be El Niño, Neutral or La Niña, are also determinant to predict ME production. Thus, the model realistically simulates the monthly variability of ME production, accounting for annual ME production and animal ME requirements. Therefore, the model was fit to optimize herd size under the assumption that, during the months when there is feed surplus, this surplus would be stored to be offered as hay during the months of feed deficit.

All the scenarios were arbitrated to quantify total ME production, and did not consider the allocation of specific animal classes in the intensified areas. The values used to parameterize this submodel were retrieved from a database of natural pastures representative of the studied region (Carvalho et al., 2017), using only forage mass and daily dry matter accumulation within the interval of two standard deviations.

Table 2
Parameters of the energy requirements submodel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/description</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>Bos taurus, Bos indicus, and their crosses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animal classes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dietary metabolizable energy content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day of year</td>
<td>0 to 365</td>
<td>Meal/kg DM</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>−35</td>
<td>(- in S)</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Live weight gain</td>
<td></td>
<td>g/d</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td>days</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Lactation phase</td>
<td></td>
<td></td>
<td>Cardoso et al. (2016)</td>
</tr>
<tr>
<td>Stage of pregnancy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calf birth weight</td>
<td>30</td>
<td>kg</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Calf mature body weight</td>
<td>450</td>
<td>kg</td>
<td>ANUALPEC/FNP (2008)</td>
</tr>
<tr>
<td>Calf weight gain</td>
<td>725</td>
<td>g/d</td>
<td>Cardoso et al. (2016)</td>
</tr>
<tr>
<td>Proportion of calf ME requirements supplied by the dam's milk</td>
<td></td>
<td>%</td>
<td>Freer et al. (2012)</td>
</tr>
<tr>
<td>Increased cow ME maintenance requirem</td>
<td></td>
<td>%</td>
<td>Freer et al. (2012)</td>
</tr>
</tbody>
</table>

Energy requirements submodel adapted from Freer et al. (2012).
Table 3
Values of the parameters of the energy production submodel.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Grassland El Niño</td>
<td>18.2</td>
<td>22.5</td>
<td>18.3</td>
<td>12.9</td>
<td>8.3</td>
<td>9.3</td>
<td>7.5</td>
<td>11.9</td>
<td>21.0</td>
<td>19.4</td>
<td>21.0</td>
<td></td>
<td>kg DM/ha/d</td>
<td>Carvalho et al. (2017)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>141.3</td>
<td>1456.1</td>
<td>1607.6</td>
<td>1657.0</td>
<td>1565.9</td>
<td>1463.2</td>
<td>1412.0</td>
<td>1319.9</td>
<td>1376.8</td>
<td>1471.3</td>
<td>1588.4</td>
<td>1551.1</td>
<td>kg DM/ha</td>
<td>Carvalho et al. (2017)</td>
</tr>
<tr>
<td>Total digestible nutrients</td>
<td>53.5</td>
<td>53.5</td>
<td>53.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>%</td>
<td>de Freitas (1975)</td>
</tr>
<tr>
<td>Neutral El Niño</td>
<td>9.9</td>
<td>12.3</td>
<td>15.2</td>
<td>16.0</td>
<td>9.7</td>
<td>12.8</td>
<td>12.4</td>
<td>7.2</td>
<td>7.1</td>
<td>14.3</td>
<td>14.3</td>
<td>13.1</td>
<td>kg DM/ha/d</td>
<td>Carvalho et al. (2017)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>1094.1</td>
<td>1189.7</td>
<td>1365.5</td>
<td>1271.0</td>
<td>1438.7</td>
<td>1294.5</td>
<td>1268.5</td>
<td>1204.6</td>
<td>1279.8</td>
<td>1303.2</td>
<td>1340.3</td>
<td>1438.9</td>
<td>kg DM/ha</td>
<td>Carvalho et al. (2017)</td>
</tr>
<tr>
<td>Total digestible nutrients</td>
<td>53.5</td>
<td>53.5</td>
<td>53.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>%</td>
<td>de Freitas (1975)</td>
</tr>
<tr>
<td>La Niña</td>
<td>5.9</td>
<td>10.3</td>
<td>11.4</td>
<td>10.1</td>
<td>5.2</td>
<td>6.5</td>
<td>10.0</td>
<td>7.2</td>
<td>6.7</td>
<td>8.0</td>
<td>7.7</td>
<td>9.2</td>
<td>kg DM/ha/d</td>
<td>Carvalho et al. (2017)</td>
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<tr>
<td>Daily dry-matter accumulation rate</td>
<td>928.6</td>
<td>1030.3</td>
<td>1034.9</td>
<td>1151.8</td>
<td>1192.5</td>
<td>1239.8</td>
<td>1220.3</td>
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<td>1198.0</td>
<td>1178.3</td>
<td>1127.8</td>
<td>1050.8</td>
<td>kg DM/ha</td>
<td>Carvalho et al. (2017)</td>
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<tr>
<td>Total digestible nutrients</td>
<td>53.5</td>
<td>53.5</td>
<td>53.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>56.5</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>54.1</td>
<td>%</td>
<td>de Freitas (1975)</td>
</tr>
<tr>
<td>Sorghum-sudangrass hybrids</td>
<td>243.9</td>
<td>208.1</td>
<td>98.8</td>
<td>44.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Schittenhelm and Schroetter (2014)</td>
</tr>
<tr>
<td>Irrigated El Niño</td>
<td>217.0</td>
<td>185.2</td>
<td>87.9</td>
<td>39.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Filho et al. (2010)</td>
</tr>
<tr>
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<td>220.8</td>
<td>143.6</td>
<td>57.6</td>
<td>33.3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Schittenhelm and Schroetter (2014); Zamfir et al. (2001)</td>
</tr>
<tr>
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<td>57.6</td>
<td>58.8</td>
<td>57.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Filho et al. (2010)</td>
</tr>
<tr>
<td>Neutral El Niño</td>
<td>154.7</td>
<td>124.1</td>
<td>54.8</td>
<td>17.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Schittenhelm and Schroetter (2014); Filho et al. (2010)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>59.5</td>
<td>57.6</td>
<td>58.8</td>
<td>57.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Schittenhelm and Schroetter (2014); Zamfir et al. (2001)</td>
</tr>
<tr>
<td>Ryegrass sowed with oat El Niño</td>
<td>40.1</td>
<td>30.2</td>
<td>44.4</td>
<td>40.0</td>
<td>41.0</td>
<td>42.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Soares et al. (2001); Macari et al. (2006)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>1000.2</td>
<td>1042.8</td>
<td>1068.8</td>
<td>1150.7</td>
<td>1233.8</td>
<td>1224.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha</td>
<td>Soares et al. (2001); Macari et al. (2006)</td>
</tr>
<tr>
<td>Forage mass</td>
<td>60.7</td>
<td>60.2</td>
<td>60.5</td>
<td>58.6</td>
<td>55.7</td>
<td>44.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Roso et al. (1999); Piazzetta et al. (2009)</td>
</tr>
<tr>
<td>Neutral El Niño</td>
<td>48.2</td>
<td>50.4</td>
<td>52.8</td>
<td>45.8</td>
<td>50.7</td>
<td>52.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Roso et al. (1999); Restle et al. (1999)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>1132.1</td>
<td>1455.5</td>
<td>1457.5</td>
<td>1693.0</td>
<td>1816.4</td>
<td>1803.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha</td>
<td>Roso et al. (1999); Restle et al. (1999)</td>
</tr>
<tr>
<td>Forage mass</td>
<td>60.7</td>
<td>60.2</td>
<td>60.5</td>
<td>58.6</td>
<td>55.7</td>
<td>44.8</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Roso et al. (1999); Piazzetta et al. (2009)</td>
</tr>
<tr>
<td>La Niña</td>
<td>22.9</td>
<td>56.8</td>
<td>45.5</td>
<td>49.9</td>
<td>51.8</td>
<td>55.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha/d</td>
<td>Frizzo et al. (2003)</td>
</tr>
<tr>
<td>Daily dry-matter accumulation rate</td>
<td>1000.2</td>
<td>1042.8</td>
<td>1068.8</td>
<td>1150.7</td>
<td>1233.8</td>
<td>1224.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg DM/ha</td>
<td>Frizzo et al. (2003)</td>
</tr>
<tr>
<td>Forage mass</td>
<td>60.7</td>
<td>60.2</td>
<td>60.5</td>
<td>58.6</td>
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<td>44.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Roso et al. (1999); Piazzetta et al. (2009)</td>
</tr>
</tbody>
</table>
of the mean.

Average total digestible nutrients were modeled considering pasture quality variability during the year. However, for the purposes of this model, these values were set as fixed among intensification levels and ENSO events (UL-Allah et al., 2014). Forage mass and daily dry matter accumulation rate were set considering their variability throughout the year according to pasture type, irrigation effect and ENSO event (Table 3), and forage allowance was defined as 10% (10 kg DM/100 kg BW; Trindade et al., 2016) for all pastures.

This submodel predicts the amount of ME monthly available according to the following equation:

\[ \text{MEA} = \left( \text{FM} + (\text{DAR} \times 30.40) \right) \times \text{TDN} \times 4.40 \times 0.82 \times \text{EFH} \]  
(1)

(adapted from the NRC, 1996)

Where MEA represents the metabolizable energy available (Mcal/ha/month); FM, forage mass (kg DM/ha); DAR, daily dry-matter accumulation rate (kg DM/ha/day); TDN, total digestible nutrients (%); and EFH, efficiency of forage harvest (%). The energy concentration (ECF) of each forage type, which is used as an input variable throughout the year in the energy requirements submodel, was obtained by the equation:

\[ \text{ECF} = \text{TDN} \times 4.40 \times 0.82 \]  
(2)

(NRC, 1996) Where ECF represents the metabolizable energy content of the forage (Mcal/kg DM); and TDN, total digestible nutrients (%).

This submodel is related with the intensification level by capturing the size of the intensified area and dynamically solving ME production throughout the year for each forage type, using the settings in Table 3. The resulting total MEA value is used as a key input variable in the herd structure submodel to predict the size of the herd that each intensification level is able to carry. Therefore, this submodel is directly related to the other submodels, because the generated information supports the other submodels.

### 2.7. Model outcomes

The model outcomes include ME production by the system, herd ME requirements, forage carrying capacity, and productivity and biological efficiency of the production system. Herd structure is given by the number of animals in each class throughout the year.

ME requirements and production are expressed in Tera calories (Tcal) and are the results of the sum of herd ME requirements and of pasture ME production, respectively throughout the year. Productivity was obtained using the equation:

\[ \text{Productivity} = \sum \text{CW} + \sum \text{CS} + \sum \text{HS} \]  
(3)

(Adapted from Davis et al., 1983 and Lamb et al., 1992)

Where productivity is kilogram of live weight produced (kg LW/ha/year); CW is kilograms of weaned calves (kg LW/ha/year); CS is kilograms cow surplus (kg LW/ha/year) and HS is kilograms of heifer surplus (kg LW/ha/year).

The biological efficiency, defined as productivity per unit of ME produced annually by the system and simulated for a 10-year horizon, was obtained by the equation:

\[ \text{Efficiency} = \frac{\text{Productivity}}{\text{ME}_1} \]  
(4)

(Adapted from Walmsley et al., 2016)

Where Efficiency is the biological performance (g LW/Mcal ME); Productivity is the total live weight produced (kg LW/ha/year) and ME$_1$ is the total amount of ME produced by the system available to the herd (Total Mael ME/ herd/year).

The conceptual model is a proposal of intensification of cow-calf systems, and not specific to a given production system or data set. In general, models of such systems cannot be submitted traditional validation procedures (Walters et al., 2016; Shane et al., 2017). For this reason, in our simulation the validation is operational, allowing to compare the results of the model with published research data and also to detect differences among the evaluated scenarios.

### 3. Results

#### 3.1. Operational validation

Model efficacy was evaluated based on the conceptual model and on the equation flow to determine if the model operated as expected. Therefore, we tested several intervals of the model parameters to determine if it responded to the changes as expected.

The herd structure submodel was sensitive to the changes at each simulation performed because its dynamics is consistent with the number of dams, pregnancy risk and survival probability, resulting in adequate and realistic proportions of the number of calves born and weaned in each intensification scenario. In addition, dam proportion was consistent and according to the age and number of calves produced, with a higher proportion of younger dams than of older dams in the herd structure. This is due to likelihood of a dam staying in the system from one year to the next if it became pregnant in the previous mating season and survived (Pang et al., 1999). Thus, in a stabilized herd, there is a higher proportion of young dams than older dams, and this biological phenomenon was adequately and consistently represented by the proposed submodel.

The simulated parameters included pregnancy risk of heifers (80 to 100%), second-calf cows (66 to 86%), and multiparous cows (70 to 90%); probability of calf survival from birth to weaning (94 to 100%); annual probability of survival of second-calf, multiparous and last-calf cows (96 to 100%); number of cows (50 to 5000); and bull to cow ratio (1.5 to 3%).

The energy requirements submodel is an adaptation of the model proposed and validated by Freer et al. (2012) for the prediction of ME requirements and ME utilization for maintenance and production, according to the recommendations of the CSIRO (2007). No quantitative individual weight gain variations were tested because the assumed output of the proposed intensification levels was pasture carrying capacity.

The energy production submodel includes the variations in forage mass, daily dry matter accumulation rate, and total digestible nutrients in order to provide adequate estimates of ME production. Therefore, increasing values of those parameters result in greater ME production (Fig. 5).

#### 3.2. Comparison of model results with published literature

The magnitude of the intensification had variable impacts on ME production (Fig. 5), on pasture carrying capacity (Fig. 6) and on system productivity (Fig. 7). These results are consistent with studies reporting that increasing intensification levels have a positive impact on the productivity of cow-calf systems (Potter et al., 1998; Beretta et al., 2002; M.D. Dill et al., 2015b; Mazzetto et al., 2015; Ruviaro et al., 2015; Li et al., 2017; Pereira et al., 2018a; P.R.R.X. Pereira et al., 2018b).

The model also showed that pasture irrigation maximizes biomass production by the system (Zamfir et al., 2001; Cosentino et al., 2012; Roccard et al., 2012; Schittenhelm and Schroeter, 2014), which may increase ME in 0.4 to 8.5%, as a function of climatic event and intensification level (Fig. 5). Li et al. (2017), evaluating the effect of irrigation on cow-calf systems, determined a 17% increase in forage biomass.

Considering the 10-year horizon, our results demonstrate average productivity values of 219 to 254 kg LW/ha/year, as a function of intensification level and the use or not of irrigation (Fig. 8). These findings corroborate with those described by El-Memari (2018) and are within the technical potential of beef cow-calf production systems in Brazil. Nevertheless, our results are greater to those found by
Potter et al. (1998), 60 to 116; Beretta et al. (2002), 38 to 81; Kopp et al. (2004), 15 to 158 and Nasca et al. (2015), 50 to 85 kg LW/ha/year. This is probably due to the strong interventions proposed using technology in our study, represented by cultivated pasture or irrigation.

In the present study, the model estimated an average biological efficiency 5.47 g LW/Mcal total ME (Figs. 7 and 8). This finding is according with the results of Zilverberg et al. (2011), who evaluated the effect of different management practices and environmental factors on the energy utilization in cow-calf systems and obtained efficiency...
values of 5 to 17 g LW/Mcal total energy. On the other hand, Calegare et al. (2009), analyzing proportion of Bos taurus in a cross-breeding system, obtained efficiency values of 35 to 45 g of product/Mcal of total ME. Although these values are higher than those obtained in our study, the results are equivalent, because we considered the ME intake of all animal classes in the herd, while Calegare et al. (2009) assumed the ME intake of only the cow-calf pair. Therefore, based on literature findings and on the production results obtained in the present study, the efficacy of proposed model for the estimation of the effects of intensification of beef cow-calf systems in the Brazilian pampa biome is

Fig. 7. Annual productivity and biological efficiency as a function of intensification level and ENSO event.

Fig. 8. Productivity and annual biological efficiency as a function of intensification level in a 10-year horizon.
demonstrated.

3.3 Herd structure

Higher intensification levels allowed to allocate a larger number of cows in the 1000-ha area. Moreover, irrigation increased pasture carrying capacity compared with the baseline system (0% intensification) and non-irrigated intensified systems (Fig. 6). Herds with higher numbers of heads required higher ME amounts (Figs. 5 and 6). Annually, the carrying capacity of the 0% intensified system was 1243, 1057 and 879 cows during El Niño, Neutral and La Niña years, respectively. In the 20% intensified system with irrigation, cow carrying capacity increased in 8.8, 18.4 and 22.4% during El Niño, Neutral and La Niña years, respectively, compared with the 0% intensified system (Fig. 6).

In the 10-year horizon, the non-intensified system (0% intensification level) presented a total carrying capacity of 10,772 cows. When intensification was simulated by the use of sudangrass in the summer, with no irrigation, and ryegrass associated with oat in the winter, carrying capacity increased in 2.8, 5.7, 8.5 and 11.4% for the 5, 10, 15 and 20% intensification levels, respectively. Moreover, the use of irrigation enhanced the effects of intensification levels on carrying capacity, which was 4.0, 7.9, 11.8 and 15.8% higher for the 5, 10, 15 and 20% intensification levels, respectively, relative to 0% intensification level (Fig. 6).

System intensification with or without irrigation resulted in higher productivity compared with the baseline scenario (0% intensification). All intensification levels resulted in higher numbers of calves and surplus cows and heifers compared with the baseline scenario. Increases of 11.5, 13.3 and 11.5% in the number of calves, and of surplus cows and heifers were obtained for the 20% intensified system with no irrigation, and of 15.9, 15.8 and 16.0% for the same level of intensification with irrigation, respectively. Increases of 8.6, 8.6 and 8.7% in the number of calves, and of surplus cows and heifers were obtained for the 15% intensified system with no irrigation, and of 11.9, 11.9 and 12.0% in the same level of intensification with irrigation, respectively. Increases of 5.7, 5.5 and 5.7% in the number of calves, and of surplus cows and heifers were obtained in the 10% intensified system with no irrigation, and of 8.0, 8.0 and 7.9% in the same level of intensification with irrigation, respectively. Increases of 2.9, 2.7 and 2.8% in the number of calves and of surplus cows and heifers were obtained for the 5% intensified system with no irrigation, and of 4.0, 4.0 and 3.8% for the same level of intensification with irrigation, respectively (Fig. 6).

3.4 Production of metabolizable energy

Annual ME production of 46.3, 39.4 and 32.7 Tcal were calculated for the 0% intensified system in El Niño, Neutral and La Niña years, respectively. In the 20% intensified system with irrigation, ME production increased in 1.7% in El Niño, 4.0% in Neutral and 8.5% in La Niña years relative to the 0% intensified system (Fig. 5). Considering the 10-year horizon, ME production in the 20% intensified system increased in 15.8% when irrigation was applied (Fig. 5). Therefore, irrigation alone accounted for 4.4% of increase in ME production.

3.5 Productivity and biological efficiency

The association of intensification level with climatic event influenced annual productivity. The non-intensified system produced 253.2, 215.1 and 179.0 kg LW/ha/year, in El Niño, Neutral and La Niña years, respectively. When the system was 20% intensified with no irrigation, productivity increased in 7.1, 15.7 and 12.9% in El Niño, Neutral, and La Niña years, respectively, while irrigation promoted further increases of 8.9, 18.7 and 22.2% in the same years compared with the 0% intensification level (Fig. 7).

In the 10-year horizon, the average productivity obtained for the non-intensified system was 219 kg LW/ha/year. Whereas 2.8 and 12.3% increases in productivity were calculated for the 5% and 20% levels with no irrigation, respectively. With further improvement of 3.9 and 15.9% in these systems when irrigation was applied (Fig. 8).

Irrigation had no influence on the biological efficiency of intensified systems calculated for the 10-year horizon, which average value was calculated as 5.47 g LW/Mcal of total ME (Fig. 8).

4. Discussion

The results of the present study demonstrate that the proposed model is able to evaluate the influence of intensification of grazing systems on metabolizable energy production, carrying capacity, productivity and biological efficiency of beef cow-calf systems over a long-term horizon. Productivity was increased in 15.9% when 20% of the grazing area was intensified and irrigated compared with the modeled non-intensified system, independently of climatic events. Although other studies evaluating the intensification of beef cow-calf systems have been carried out (Ash et al., 2015; Monjardino et al., 2015), to the best of our knowledge, the present study is the first to propose a model to evaluate the biological impacts of the intensification such systems using the irrigation of sudangrass (C4 tropical species) in the summer and ryegrass associated with oat in the winter, taking into account the effects of ENSO phenomena during a 10-horizon.

The aim of the model was to evaluate how the influence of system intensification affects the productivity and the efficiency metabolizable energy utilization of beef cow-calf systems in a 10-year horizon. In addition, this dynamic model allows modeling system intensification under different biological animal constraints, such as productive, reproductive and survival parameters, and management (e.g., times of management practices) over long-term horizons. The model represents a 1000-ha grazing system with different intensification scenarios and fits herd size allocation as a function of forage ME production at each intensification level and herd energy requirements.

Higher intensification levels resulted in higher annual forage biomass production, increasing pasture carrying capacity, as the intensification level is associated with the size of the intensified area, which increase the amount of ME produced by the system, and consequently, its carrying capacity. As a consequence of the higher number of dams allocated, the number of calves and of surplus cows and heifers is increased, determining higher productivity.

Our results show that beef cow-calf systems in the Brazilian pampa biome may generate an average productivity of 219 kg LW/ha/year over a 10-year horizon, considering ENSO events. However, the adoption of intensification processes, such as the irrigation of annual summer pastures and the establishment of winter pastures (with no irrigation), allows increasing herd productivity in 3.9, 7.9, 11.9 and 15.9% when 5, 10, 15 and 20% intensification levels are applied compared with a non-intensified system. The differences between the baseline (0% intensified) and the intensified scenarios with no irrigation are explained by the higher biomass production of sudangrass between January and April, and of ryegrass associated with oat between June and November. However, the irrigated intensification levels systems presented higher carrying capacity. These results are explained by the fact that irrigation ensures higher ME production levels, which may be used to face critical feed allowance gaps (Heard et al., 2012; Schittenhelm and Schroetter 2014). Pasture irrigation prevents hydric stress effects on plants and minimizes production seasonality during the year (Jensen et al., 2010), resulting in stable ME production, and consequently, higher productivity (Monjardino et al., 2015). The model also demonstrated that productivity is determined by carrying capacity per area, and not by individual animal performance, because herd ME requirements remained constant among the different intensification scenarios. On the other hand, ME production is dynamic as it is influenced by climate, forage species, month of the year and proportion of
area used for each type of pasture.

Our results showed that El Niño, Neutral and La Niña events resulted in higher, intermediate and lower biomass production and consequently ME production, respectively, regardless of irrigation. This may be explained by the fact that, during El Niño years, rainfall is higher than the climatological average and, in La Niña years, below the average, especially during the spring and early summer (Gelcer et al., 2013), which may affect interannual variability of pasture biomass production (Jacobssen et al., 2003). Independently of climatic event, irrigation promoted higher ME production at all intensification levels; however, these differences were more pronounced in La Niña years and less marked in El Niño years. Therefore, La Niña has stronger influence on the system carrying capacity because periods of drought are more frequent during this climatic event. On the other hand, during El Niño years, this effect is attenuated due to the higher incidence of rainfall. In the 10-year horizon evaluated, the effect of irrigation on ME production was remained constant, with 4.0% higher ME production in the 20% intensification level with irrigation (464.3 Tcal) than without irrigation (446.6 Tcal). Although irrigation may have a stronger effect on biomass production over the long-term horizon, these results are explained by the probability of occurrence of ENSO events in the studied region, of 50, 30 and 20% for Neutral, El Niño and La Niña events, respectively (Matzenauer et al., 2008; Gelcer et al., 2013).

Despite the lower probability of occurrence of La Niña event and the fact that irrigation was used only during one-third of the year, the effect of irrigation on ME production was still observed in the 10-year horizon. In the systems with 5, 10, 15 and 20% intensification levels, irrigation increased ME production in 0.4, 0.9, 1.3 and 1.7% in El Niño and 1.1, 2.1, 3.1 and 4.0% in Neutral years, respectively. However, the most pronounced differences were determined in La Niña years, of 2.3, 4.5, 6.6 and 8.5%, due to the occurrence of droughts and possibly contributed to the higher biomass production of irrigated intensified systems determined in the 10-year horizon (Hopplewski and Halpert, 1987; Cunha, 1999; Grimm et al., 2006; Haylock et al., 2006). Montaño-Bermudez and Nielsen (1990) and Beretta et al. (2002) obtained biological efficiencies of 28.3 and 24.0 g LW/Mcal of ME, which are 81 and 77% higher than that obtained in the present study, which efficiency calculation was on the ME requirements of the entire herd. On the other hand, Montaño-Bermudez and Nielsen (1990) only considered ME maintenance requirements, whereas Beretta et al. (2002) evaluated the efficiency of a breeding-to-finishing system. Studies have demonstrated that the biological efficiency of cow-calf systems is lower than that of breeding-to-finishing systems, which, in turn, is lower than that of finishing systems (Nasca et al., 2015). Therefore, our results may reflect what is expected to occur in cow-calf systems, and are in agreement with the efficiency values obtained by Calegare et al. (2009) and Zilverberg et al. (2011), who reported efficiencies of 35 to 45 g of product/Mcal of total ME and of 5 to 17 g LW/Mcal total energy, respectively.

According to SEAPI (2013), in the state of Rio Grande do Sul, irrigation may potentially be extended to beef cattle production areas. However, there are few studies on the influence of irrigation on the energy production, carrying capacity, productivity and biological efficiency of beef cattle production systems.

The results of the present study do not allow us to recommend the use of pasture irrigation to enhance the productivity of cow-calf systems. However, the evaluated model evidenced that the productivity of cow-calf systems is directly proportional to the number of dams the system is capable of carrying, when productive, reproductive and survival parameter values are maintained constant. Moreover, carrying capacity is directly proportional to the amount of energy produced by the system. Therefore, the proposed model may be used as a tool to understand the influence of intensification and climatic events on the energy production of cow-calf systems in order to apply intensification practices to enhance the carrying capacity and consequently, the productivity of such systems.

Computational models are indispensable tools in theoretical and applied livestock production systems and their interactions with climatic phenomena (Walters et al., 2016). However, important limitations remain when using these models to develop general, predictive theory and for the support and management of actual livestock systems under changing conditions (Grimm and Berger, 2016). Even for the same system, the pathways taken in modeling can be extremely different because the development of models is influenced by differences in the questions, availability of data, and consideration of specific expert knowledge, in addition to the experience, background, and modeling preferences of the modellers (Thiele and Grimm, 2015).

A possible limitation of the proposed model is its deterministic nature, because forage mass and daily accumulation rate per month of the year, within each pasture type and within climatic event, are modeled to be constant within each level of intensification. However, in biological terms, it would be more appropriate to assume biomass growth as a function of a probability based on the environmental conditions of a specific system.

Another possible limitation of the model is to characterize the El Niño, Neutral and La Niña climatic events as rainfall above, below and within the climatological average, respectively. Perhaps, it would be more appropriate to consider the chaotic dynamic nonlinear (stochastic) nature within each ENSO event. Nevertheless, there is scientific evidence to support this classification (El Niño, Neutral and La Niña) in terms of the probability of occurrence in southern Brazil (Fontana and Berlato, 1997; Grimm et al., 1998; Marengó and Oliveiera, 1998; Fedorova and Carvalho, 2006; Berlato and Fontana, 2003; Gelcer et al., 2013).

The deterministic nature of our model makes it difficult to assess the effects of intensification in a dynamic approach, that is, in each year over the 10-year horizon. This could be considered as a limitation of the model. However, our model is based on the assumption that in the 10-year time horizon, there is a probability of occurring in 20, 30 and 50% the event La Niña, El Niño and Neutral, respectively, in southern Brazil (Matzenauer et al., 2008; Gelcer et al., 2013). These probabilities of occurrence, based on scientific evidence, justify the evaluation of the intensification effects in each climatic phenomenon (La Niña, El Niño and Neutral) and the weighted effects in 10 years.

In short, we tweaked our model to appear correct with the assumptions that certain model mechanisms are either more or less important than they actually are in real cow-calf production systems. To some degree, this type of tweaking is inherent to any type of modeling, and the art of modeling that focuses on a mechanistic understanding of systems requires limiting such tweaking as much as possible (Grimm and Berger, 2016).

Despite the limitations of the model, they do not diminish the importance of our results, since the model represents the complexity that characterizes beef cow-calf systems and reflects what is expected to occur in biological systems.

5. Conclusions

The developed model allows to understand the productive response to different intensification levels of beef cow-calf systems. The main productive response was the increase in the number of dams in the herd, especially as a result of the use of irrigation. This study proposes different levels of intensification, using cultivated pastures and irrigation, to increasing the productivity of beef cow-calf systems in southern Brazil. However, an economic analysis, considering the cycle of beef cattle prices, is required when evaluating the adoption of the proposed intensification processes.

Declaration of Competing Interest

None.
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Supplementary materials


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