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Effects of changes in finishing diets and growth technologies on animal growth performance and the carbon footprint of cattle feeding: 1990 to 2020

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ABSTRACT

Objective: Our objective was to estimate the effects of changes in feedlot diets and the availability of performance-enhancing technologies on growth performance and the carbon footprint of cattle feeding between 1990 and 2020.

Materials and Methods: A model was developed to represent feedlot diets and technologies used in 1990 versus 2020 and evaluate changes in growth performance and carbon footprint. Byproduct feeds became more common between 1990 and 2020; thus, corn and dry roughage inclusion rates decreased. Estradiol-only implants and monensin were the available technologies in 1990, whereas in 2020 use of implants with combinations of trenbolone acetate and estradiol, monensin, and ractopamine hydrochloride (in the final 28 to 42 d) were common.

Results and Discussion: In both 1990 and 2020 use of all available technologies increased final BW, ADG, G:F, and hot carcass weight compared with no technology. From 1990 to 2020 initial BW, final BW, ADG, G:F, hot carcass weight, and daily DMI increased. Total days on feed increased by 44 d from 1990 to 2020. Compared with no technology, use of technologies in both 1990 and 2020 decreased total greenhouse gas emissions per animal (CO_2 equivalent, CO_2e). Because cattle had greater days on feed in 2020, all sources of greenhouse gas emissions per animal increased compared with the values estimated in 1990. However, when expressed as CO_2e/kg of BW gain, emissions have decreased by 4.4% because of greater total BW gain in 2020 versus 1990.

Implications and Applications: Feedlot cattle decreased relative emissions from 4.78 kg of CO_2e/kg of BW gain in 1990 to 4.58 kg of CO_2e/kg of BW gain in 2020. Overall, feedlots in 2020 produced 47.5% more BW gain with 1.4% less cattle, while only increasing total CO_2e by 39.5%. Therefore, changes in available technologies and diet formulations have improved efficiency and reduced the carbon footprint of feedlot cattle production in the past 30 yr.

Key words: beef cattle, carbon footprint, emissions, feedlot, sustainability

INTRODUCTION

As the global population grows and demand for beef increases, management practices must evolve to accommodate changes in feedstuff availability, enhance growth efficiency, and address consumer concerns regarding the environmental sustainability of livestock production. To facilitate these enhancements, research has focused on developing technologies and animal management techniques to improve growth performance and accommodate the needs of an ever-changing beef industry. For example, between 1990 and 2020 there have been distinct changes in feedlot cattle diets and an increase in the availability and use of growth-promoting technologies. Grain-milling byproducts such as corn gluten feed and distillers grains have become common ingredients in feedlot cattle diets (Samuelson et al., 2016), yet these ingredients were scarcely available in 1990. Availability and use of growth-promoting technologies such as implants, ionophores, and β-adrenergic agonists (**βAA**) have also changed significantly over the past 30 yr as research has been conducted to refine the management practices surrounding their administration and develop new products.

Consumers are continually expressing greater concern for the effect that beef cattle production has on the environment and how this may affect sustainability of the beef production system. Methane (CH_4), CO_2, and N_2O are greenhouse gases emitted as waste products from inef-

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ficiencies of ruminal fermentation, as metabolic byproducts, and from degradation of manure. Calculating a carbon footprint (C-footprint) adjusts each of the greenhouse gases to a common CO_2 equivalent (**CO_2e**) to represent the total potential for global warming (**GWP**).

Changes in diets and the use of growth-promoting technologies have improved growth performance of beef cattle compared with natural beef production systems (Wileman et al., 2009). In addition, these improvements in growth performance have increased feed efficiency and reduced the environmental impact of raising cattle in feedlots (Stackhouse-Lawson et al., 2013). Our objective was to estimate the effects of current feedlot diets and technologies on animal growth performance and the C-footprint of cattle feeding between 1990 and 2020.

MATERIALS AND METHODS

Because no live animals were used, this research was not evaluated by the Institutional Animal Care and Use Committee at West Texas A&M University. For this study, a model was developed to represent typical feedlot finishing diets (Table 1) fed to cattle in 1990 and 2020 using dietary ingredients that had a C-footprint reported in the literature (Adom et al., 2012). The diets contained steam-flaked corn, alfalfa hay, soybean meal, tallow, and supplement in 1990, and in 2020 wet distillers grains plus solubles (**WDGS**) replaced a portion of steam-flaked corn and all of soybean meal. Steam flaking was used in both years because it was the most widely used processing method for corn according to Galyean (1996) and Samuelson et al. (2016). The 20.0% of dietary DM inclusion of WDGS in the 2020 diet was selected based on the most recent consulting nutritionist survey conducted in 2015 (Samuelson et al., 2016). Technologies reported in the 1990 model included no technology, growth-promoting implants (estrogen only), ionophores, and the use of both implants and an ionophore in combination. In contrast, the 2020 model included no technology; implants (estrogen and androgen combination); ionophores; implants and ionophores in combination; βAA; and the combination of implants, ionophores, and βAA. Ractopamine hydrochloride (**RH**) was used to model the performance improvements associated with βAA administration because it was the only βAA used in the United States in 2020. Monensin sodium was selected to describe the effects of ionophores in both 1990 and 2020 because it was reported to be the most widely used ionophore in feedlot cattle diets (Russell and Strobel, 1989; Samuelson et al., 2016). Although not every possible combination of technologies is presented, those reported in the model represent commonly used technologies in the feedlot industry in the last 30 yr.

For the 1990 model, a review of feedlot cattle studies published in the *Journal of Animal Science* between 1990 and 1995 and closeout records from the 1997 Kansas State University Focus on Feedlots Reports (Kuhl, 1997) were conducted to establish values for comparison of growth performance under different management conditions. Manuscripts were excluded if they contained treatments that used programed feeding, where cattle were fed to achieve a certain ADG and therefore *ad libitum* intake was not achieved. In addition, manuscripts that did not contain growth performance measurements were excluded. The 1997 Kansas State University Focus on Feedlots Reports were used because they represented the earliest publicly available date for cattle fed in the 1990s. A total of 9 publications and 3 Kansas Focus on Feedlots Reports were used in a weighted average to calculate initial and final BW and ADG from the selected study treatment means (Lewis et al., 1990; Zinn, 1990; Xiong et al., 1991; Zinn, 1991; Ham et al., 1994; Bauer et al., 1995; Krehbiel et al., 1995b; Ladely et al., 1995; Ludden et al., 1995). Baseline DMI was determined using the DMI prediction equation proposed by the NASEM (2000, DMI = 4.54 + 0.0125 × initial BW). Gain-to-feed ratio was calculated by dividing the ADG by DMI. These values were used to model baseline growth performance for cattle receiving both an implant and monensin. Performance (final BW and ADG) for cattle receiving an implant only, monensin only, and no technology (no implant, no monensin) was then back-calculated by removing the improvements in performance associated with each technology from the baseline.

Initial BW was not adjusted based on the different technologies used. However, final BW was reduced by 35 kg when implants were not used (no technology and monensin only) in accordance with the NASEM (2000). The DMI was decreased by 6% for the non-use of implants (NASEM, 2000) and increased by 4% when monensin was not included in the diet (Galyean et al., 1992). The ADG

Table 1. Ingredient and nutrient composition of typical feedlot finishing diets fed in 1990 and 2020

Item	1990 Diet	2020 Diet
Ingredient, % of DM		
Steam-flaked corn	76.4	65.4
Alfalfa hay, mature	13.0	9.0
Wet distillers grains plus solubles	—	20.0
Soybean meal	5.0	—
Tallow	2.5	2.5
Supplement	3.1	3.1
Tabular nutrient estimate, DM basis		
CP, %	12.50	15.42
Fat, %	5.17	6.87
Starch, %	66.67	51.35
NDF, %	14.96	15.93
Calcium, %	0.64	0.82
Phosphorus, %	0.25	0.35
NE_m,[1] Mcal/kg	2.22	2.34
NE_g,[1] Mcal/kg	1.53	1.63

[1]Based on tabular values reported by NASEM (2016).

was decreased by 1.5% for cattle that did not receive monensin (NASEM, 2000) and 17.0% (Duckett and Andrae, 2001) for cattle that did not receive estrogenic implants. The performance changes associated with estrogenic implants were chosen from Duckett and Andrae (2001) because they represented the available technology in 1990, as use of an implant containing estrogen only was a common management practice during this time. The effects of both monensin and implant on DMI and ADG were assumed to be additive. The total number of days on feed (**DOF**) was calculated for each group by dividing the total BW gain by the ADG and is similar to the selected reference studies. Dressing percentage for the all technology group was set at 63.0% of final BW (personal communication, Ty Lawrence, West Texas A&M University, Canyon, TX). In the groups that did not receive an estrogenic implant, DP was increased by 0.16% points (Reinhardt and Wagner, 2014). Hot carcass weight was calculated by multiplying the DP by the final BW.

To model growth performance of cattle fed in 2020, baseline values were determined using a literature search of feedlot research published in the *Journal of Animal Science* between 2015 and 2020 and monthly closeout reports from the 2020 Kansas Focus on Feedlots (Waggoner, 2020). Manuscripts were eliminated from the data pool if monensin, a combination implant, or RH was not used. A total of 10 journal articles were used (Russell et al., 2016; Schwandt et al., 2016; Stokes et al., 2016; Thompson et al., 2016; Genther-Schroeder et al., 2018; Müller et al., 2018; Budde et al., 2019; Teixeira et al., 2019; Warner et al., 2020; Wellmann et al., 2020), and a weighted average between the journal articles and the Kansas reports was used for initial BW, final BW, and ADG. Dry matter intake was calculated using the equation DMI = 3.830 + 0.0143 × ISBW described for use in feedlot steers by the NASEM (2016), where ISBW is initial shrunk BW. Baseline values represented the use of all available technologies in 2020 (monensin, a combination implant, and RH). From these values, the performance for the monensin, implant and monensin, implant, and no technology groups were calculated by removing the performance enhancements associated with each technology.

In the groups that did not receive an implant in 2020, final BW was decreased by 7.46% and ADG was decreased by 20.0% as reported for implants containing a combination of androgenic and estrogenic hormones by Duckett and Andrae (2001). For the non-implanted cattle, G:F was decreased by 15.6% (Duckett and Andrae, 2001). For the cattle not fed monensin, there were no adjustments to initial or final BW (Duffield et al., 2012). Average daily gain of cattle not fed monensin was decreased 2.5%, and DMI was increased by 3.2% as described by Duffield et al. (2012). Based on previous research conducted by Beck et al. (2014), additive effects were assumed when using implants and monensin in combination.

Ractopamine hydrochloride was assumed to be fed during the final 28 d before slaughter according to practices commonly used by feedlot nutritionists (Samuelson et al., 2016) and within label recommendations. Excluding RH decreased final BW by 1.3% and ADG by 15.3% compared with diets with RH (Gruber et al., 2007). The model did not adjust DMI for cattle fed RH, which agrees with the majority of published literature (Schroeder et al., 2004; Abney et al., 2007; Quinn et al., 2008; López-Carlos et al., 2010).

The effects of RH, monensin, and implants on animal performance were also assumed to be additive in the 2020 model (Bryant et al., 2010). Dressing percentage for the all technology group was increased to 64.0% in the 2020 model (personal communication, Ty Lawrence). Based on data published by Quinn et al. (2016), the DP of cattle not fed RH was decreased by 0.34% points. In addition, if cattle were not provided a combination implant, DP was decreased by 0.32% points (Reinhardt and Wagner, 2014).

A C-footprint analysis was also conducted and included CO_2e sources: enteric CH_4, manure CH_4, and nitrous oxide (N_2O); indirect N_2O production from feedyard ammonia emissions, processing of grain, and transport of feed and manure (Cole et al., 2020b). The C-footprint of feed equipment and facilities was not included in our analyses. Animal respiratory CO_2 emissions and net emissions of soil-C from manure application were assumed to be zero. Animal respiration CO_2e is not a net source of greenhouse gas (Steinfeld et al., 2006; Cole et al., 2020b), and there is only a marginal decrease in soil-C on land used to produce crops the animals consumed and where manure was applied and respiratory losses are derived (Schlesinger and Amundson, 2018; Cole et al., 2020b).

All greenhouse gas emissions were converted to constant CO_2e. We used the GWP of 1 for CO_2, 25 for CH_4, and 298 for N_2O (IPCC, 2006, 2019). In our calculation of the C-footprint, we estimated the GWP of natural gas used in the steam flaking process to be 25 × CO_2. A 5-region C-footprint analysis of crops fed to dairy cattle was conducted by Adom et al. (2012). The analysis included the C-footprint of herbicides, fertilizers, and so on that were used in crop production, but the C-footprint of equipment used in the farming process was not included. The C-footprint reported by Adom et al. (2012) varied by region; thus, the average of the Great Plains and Midwest regions were used in the current C-footprint analysis because most cattle on feed in the United States are fed within these regions. Therefore, the following geometric mean C-footprints were used: (1) corn grain, 390 kg of CO_2e/1,000 kg of DM; (2) alfalfa hay, 200 kg of CO_2e/1,000 kg of DM; (3) soybean meal, 460 kg of CO_2e/1,000 kg of DM; (4) miscellaneous feed additives used the same value as soybean meal (460 kg of CO_2e/1,000 kg of DM); and (5) WDGS, 330 kg of CO_2e/1,000 kg of DM. It is likely that there are differences in the C-footprint of ingredients produced in 1990 versus 2020; however, these differences are not known with certainty, and the C-footprints used in the analyses were those reported by Adom et al. (2012).

The C-footprint of distillers grains production is variable, depending on production methodology and assumptions used in the calculations (Kim and Dale, 2002; Searchinger et al., 2008; Hünerberg et al., 2014). The proportions of the total C-footprint for grain ethanol production can be assigned to ethanol and the byproduct distillers grains based on mass, energy content, or economic value. Therefore, it is unclear what proportion of the C-footprint of ethanol should be allotted to the ethanol industry and what proportion should be allotted or credited when using an ethanol byproduct in cattle feeding, such as WDGS. To equally distribute the C-footprint of WDGS across both industries by mass, we assigned 50% of the C-footprint to the ethanol industry and 50% to the beef industry (total C-footprint of WDGS is 660 kg of CO_2e/1,000 kg of DM). Therefore, in the present C-footprint analysis, we assumed the C-footprint of WDGS was 330 kg of CO_2e/1,000 kg of DM.

Enteric CH_4 emissions were calculated using the feedlot enteric CH_4 model used in the USDA-OCE 2014 publication (Powers et al., 2014). The model assumes that the Ym (CH_4 production as a percentage of gross energy intake) is 3.0% (IPCC, 2006); however, adjustments are made based on ionophore inclusion, supplemental fat inclusion, grain type, and grain concentration. In the instance where monensin was included in the diet, the Ym was adjusted down in the equation for enteric CH_4. Methane production in grams per day is then calculated from the adjusted Ym.

Manure CH_4 production was determined from volatile solid (**VS**; i.e., OM) excretion using the methods of IPCC (2006, 2019), where CH_4 production = VS excretion × the maximum potential CH_4 emission (Bo) × the CH_4 conversion factor (MCF). The MCF is the percentage of Bo emitted and is based on manure handling factors and environmental conditions. For our calculations, VS excretion was estimated from DMI and OM digestibility (assumed to be 72% for these diets), and we assumed the diets contained 95% OM. Assuming the environmental conditions were a drylot in a temperate environment, a Bo of 0.19 m^3/kg of VS and an MCF of 1.5% were used (IPCC, 2006, 2019).

Nitrogen excretion was calculated as the difference in N intake and N retention from ADG and BW (NASEM, 2016). Direct N_2O emissions from manure were estimated to be 2.0% of N excreted (IPCC 2006, 2019), whereas the indirect N_2O emissions were estimated assuming that 65.0% of the N excreted was lost as ammonia (Todd et al., 2008) and, subsequently, that 1.0% of the ammonia-N was lost as N_2O (IPCC 2006, 2019). The amount of enteric N_2O emissions only accounts for less than 0.5% of total CO_2e (Parker et al., 2018; Cole et al., 2020a). The quantity of manure collected and transported to be field applied was estimated based on Buttrey et al. (2012), where the quantity of manure DM collected from treatment pens was reported. We estimated the DM content of the collected manure to be 65.0%, which was used to calculate the total quantity of manure collected and land applied. For simplicity, we assumed that all manure was transported a common distance of 20 km.

The C-footprint of transporting feed grains to the feedlot and to collect and transport manure to fields for application were calculated assuming a constant energy cost of 149.6 kg of CO_2e/t-km (Hünerberg et al., 2014). We estimated that all feedstuffs excluding WDGS were transported an average of 200 km to the feedlot. Wet distillers grains plus solubles are typically not trucked long distances to be fed; thus, we assumed they were hauled 50 km. The subsequent manure was hauled an average of 20 km, and the average distance to haul feed from the mill to the feed bunk was 3.2 km/1,000 kg of feed DM. Our estimates were based on a 50,000-animal-capacity feedlot with 130 ha of cattle pen area. The feed delivery logistics that we used were described by da Silva et al. (2019) and Ponce et al. (2019), who estimated bulk densities of the diet and DM concentration and assumed a DMI.

RESULTS AND DISCUSSION

Because the performance and C-footprint values reviewed in this study were based on deterministic model estimates, no statistical analysis was conducted. Therefore, all data comparisons discussed will include consideration of numerical differences only.

Dietary Changes from 1990 to 2020

The ingredient and nutrient composition of feedlot diets in 1990 versus 2020 is presented in Table 1. One of the major dietary changes of note from 1990 compared with 2020 is the inclusion of fibrous grain-milling byproducts as a replacement for more expensive sources of energy and CP such as steam-flaked corn and soybean meal. High concentrations of digestible fiber and protein present within these feedstuffs allow a portion of the high-starch grains traditionally used in feedlot diets to be replaced, thus in some instances improving growth performance of cattle (Hussein and Berger, 1995; Buttrey et al., 2013; Ponce et al., 2019) while potentially mitigating ruminal acidosis (Krehbiel et al., 1995a). Although distillers grains were fed in limited amounts 100 yr ago, the increased demand for grain alcohol as a fuel source has made this feedstuff more widely available (Klopfenstein et al., 2008). More recently, increased use of artificial sweeteners and oils has also increased the availability of wet corn gluten feed from the wet milling of corn.

Because use of ethanol byproducts such as WDGS has increased, the cost per unit of dietary CP has decreased, thereby resulting in the 2020 feedlot diets having greater CP compared with 1990 (15.42 vs. 12.50% CP on a DM basis for 2020 and 1990, respectively). In a survey conducted by Galyean (1996), dietary CP ranged from 12.5 to 14.4% of DM, and by 2016, Samuelson et al. (2016) reported recommended CP concentrations ranged from 13.0 to 14.3% of DM in finishing diets. The slightly greater CP used in the 2020 model than that reported by Samuelson et al. (2016) is likely because urea was added to the diet in an effort to meet cattle requirements for RDP when feeding diets using WDGS as the sole byproduct. However, Samuelson et al. (2016) also identified a maximum tolerable concentration of 20.0% CP in finishing cattle diets and suggested that it is possible that some nutritionists were using greater than the recommended CP concentrations described previously because of the increased inclusion of high CP byproducts such as WDGS. Therefore, the authors felt the CP concentration of 15.42% was within the acceptable range for the 2020 diet.

In addition to changes in dietary CP, differences in both fat and starch concentrations from 1990 to 2020 are likely a function of incorporating WDGS into the diet. For example, dietary fat concentrations increased from 1990 to 2020 (5.17 vs. 6.87%), despite similar concentrations of added fat from tallow, yellow grease, or other fat sources. According to the NASEM (2016), steam-flaked corn, soybean meal, and WDGS contain 3.19, 1.88, and 10.84% fat, respectively, suggesting that the greater fat concentration in the 2020 diet is a function of the greater contribution of fat from WDGS, as this byproduct replaced both steam-flaked corn and soybean meal in the diet. In contrast, dietary starch concentrations decreased (66.67 and 51.35% starch in 1990 and 2020, respectively) as WDGS replaced steam-flaked corn in the diet. The process of ethanol production uses starch as the main substrate for fermentation, thereby decreasing starch and concentrating the remaining fiber, protein, and fat within residual byproducts such as WDGS (Bothast and Schlicher, 2005). Another consequence of the addition of byproducts to the current diets is greater concentrations of dietary phosphorus, which required greater inclusion of a supplementary source of calcium to maintain a 2:1 ratio of Ca:P. Overall, the concentration of CP, fat, and fiber has increased and starch has decreased between 1990 and 2020, resulting in greater net energy concentrations in 2020 compared with 1990.

Technology Effects on Cattle Growth and Emissions

Administration of anabolic implants is a common management practice used to increase ADG of feedlot cattle and has been widespread since the development of diethylstilbestrol in 1957 (Raun and Preston, 2002). Just before 1990, trenbolone acetate was approved for use in growth-promoting implants for feedlot cattle (FOIA, 1987). Trenbolone acetate is a synthetic anabolic steroid that has 3 to 5 times the androgenic activity and 8 to 10 times the anabolic activity of testosterone (Bouffault and Willemart, 1983). A common management practice today includes the use of combination implants containing both estrogen and trenbolone acetate. The most recent survey describing implant use in beef cattle indicates that 92.3% of all feedlot cattle receive at least one implant during their lifetime (USDA-NAHMS, 2013). Growth-promoting implants increased ADG, final BW, hot carcass weight (**HCW**), DMI, and G:F in 1990 (Table 2) and 2020 (Table 3). In 1990 DP was decreased when an implant was used. However, the use of combination implants in 2020 increased DP. Use of estrogenic compounds, androgenic compounds, or both, increases DMI, which could increase gut fill and subsequently reduce DP (NASEM, 2000). However, when used alone or in combination with estrogen, greater protein deposition within the carcass from administration of trenbolone acetate could offset the contribution of gut fill and increase DP (Duckett and Andrae, 2001). Furthermore, because the use of implants increased ADG at a similar proportion to the increase in final BW, the total number of DOF was comparable (0 additional DOF in 1990 and 1 in 2020) between cattle receiving either no technology or implants in both 1990 and 2000. The greater DMI in 1990 and 2020 with the use of implants caused manure production, N excretion, and enteric CH_4 production to increase. However, when calculated per kilogram of total BW gain (data not shown), manure production, N excretion, and enteric CH_4 production all decreased.

Ionophores are a feed additive used to improve feed efficiency (Goodrich et al., 1984) and animal health by decreasing the risk for subclinical acidosis (Stock et al., 1995; McGuffey et al., 2001; Birkelo, 2003; Erickson et al., 2003). Ionophore use has been widespread throughout the feedlot industry for many years (Galyean, 1996; Samuelson et al., 2016). Monensin sodium is the most commonly used ionophore (Samuelson et al., 2016) and was originally approved for use in beef cattle in 1975 (Goodrich et al., 1984). In addition to growth performance and health benefits, monensin has the potential to reduce CH_4 emissions (Tedeschi et al., 2003; McGinn et al., 2004; Tedeschi, 2011; Hemphill et al., 2018). Increased growth performance and decreased CH_4 production observed in cattle consuming monensin are accomplished primarily via the reduction of gram-positive bacteria in the rumen (Goodrich et al., 1984; Cheng et al., 1998; Birkelo, 2003). Monensin does not directly inhibit methanogen growth but inhibits H_2-producing bacteria and limits the total H_2 available for methane production (Chen and Wolin, 1979). Furthermore, monensin reduces CH_4 production by inhibiting the decomposition of formate that is produced during the breakdown of pyruvate (Van Nevel and Demeyer, 1977).

When cattle were fed monensin as the only performance-enhancing technology, final BW and HCW were not different compared with no technology for either of the time periods evaluated. In 1990 and in 2020, feeding monensin increased ADG by 0.01 kg. Inclusion of monensin in the model also decreased DMI by 0.34 and 0.24 kg in 1990 and 2020, respectively. The minor change in ADG combined with decreased DMI resulted in a 5.6% increase in G:F in 1990 and 2.7% in 2020 when monensin was used compared with no technology. The improvement in G:F decreased the DOF by 3 d in 1990 and 1 d in 2020. The reduction in DMI resulted in decreased manure production, N intake,

Table 2. Growth performance model for feedlot cattle finished using technologies available in 1990

Item	No technology	Imp[1]	Mon[2]	Imp and Mon
Initial BW, kg	335	335	335	335
Final BW, kg	500	535	500	535
Days on feed, d	137	137	134	135
ADG, kg	1.21	1.46	1.23	1.48
DMI, kg	8.55	9.08	8.21	8.73
G:F	0.142	0.161	0.150	0.170
DP, %	63.16	63.00	63.16	63.00
HCW,[3] kg	316	337	316	337
Enteric CH_4				
g/d	80.96	85.98	74.75	79.49
L/kg of DMI	13.22	13.22	12.72	12.72
Total N balance during entire feeding period				
N intake, kg	23.43	24.88	22.00	23.57
N excreted, kg	20.56	21.53	19.13	20.25
Ammonia-N, kg	15.23	16.17	14.30	15.32
Total manure excretion during entire feeding period				
Manure, kg of DM/animal	273	290	256	275
Manure, kg as is/animal	420	446	394	422

[1]Cattle received a growth-promoting implant that contained estradiol twice during the finishing period.

[2]Cattle received monensin.

[3]HCW = hot carcass weight.

Table 3. Growth performance model for feedlot cattle finished using technologies available in 2020

Item	No technology	Imp[1]	Mon[2]	Imp and Mon	RH[3]	Imp, Mon, and RH
Initial BW, kg	360	360	360	360	360	360
Final BW, kg	602	647	602	647	610	655
Days on feed, d	182	183	181	179	185	179
ADG, kg	1.33	1.56	1.34	1.60	1.35	1.65
DMI, kg	8.89	9.28	8.65	8.98	8.94	8.98
G:F	0.150	0.172	0.154	0.179	0.154	0.184
DP, %	63.34	63.66	63.34	63.66	63.68	64.00
HCW,[4] kg	381	412	381	412	388	419
Enteric CH_4						
g/d	87.36	91.20	81.74	84.85	87.85	84.85
L/kg of DMI	13.72	13.72	13.20	13.20	13.72	13.20
Total N balance during entire feeding period						
N intake, kg	39.92	41.90	38.63	39.66	40.81	39.66
N excreted, kg	36.14	37.97	35.00	35.65	37.11	35.59
Ammonia-N, kg	25.95	27.23	25.11	25.78	26.52	25.78
Total manure excretion during entire feeding period						
Manure, kg of DM/animal	377	396	365	375	385	375
Manure, kg as is/animal	580	609	561	576	593	576

[1]Cattle received a growth-promoting implant that contained trenbolone acetate and estradiol twice during the finishing period.

[2]Cattle received monensin.

[3]Cattle received ractopamine hydrochloride the last 28 d of feeding.

[4]HCW = hot carcass weight.

and enteric CH_4. Likewise, monensin has been reported to decrease the dietary gross energy lost as CH_4 in beef cattle (Ranga Niroshan Appuhamy et al., 2013; Hemphill et al., 2018).

When used together, the effects of both a growth-promoting implant and monensin were additive. Therefore, final BW of cattle in the implant and monensin group increased by 35.0 kg in 1990 (Table 2) and 45.0 kg in 2020 (Table 3) compared with no technology. Using both implants and monensin increased ADG by 0.27 kg in 1990 and 2020. Implants typically increase DMI and monensin decreases DMI; thus, using both technologies together resulted in a slightly increased DMI in 1990 (8.55 vs. 8.73 kg) and in 2020 (8.89 vs. 8.98 kg) when compared with not using technologies. As implants and monensin both increase G:F when used independently, the G:F is further increased in relation to no technology when the 2 technologies are used in combination. Because of these improvements in efficiency, enteric CH_4, excreted N, and manure output were all decreased when implants and monensin were used in combination.

Most recently, provision of a βAA for the last 28 to 42 d of the finishing period has become prevalent in the feedlot industry (Samuelson et al., 2016). β-Adrenergic agonists increase lean tissue growth by binding to β-adrenergic receptors present in the plasma membrane of both muscle and adipose tissue, which initiates a signaling cascade that results in lean tissue hypertrophy (Lynch and Ryall, 2008). The mechanism of lean muscle growth is not fully understood but could be because of increased protein synthesis, decreased protein degradation, or both (Smith et al., 1989). Ractopamine hydrochloride was first approved in 2003, and in 2020 was the only βAA used in the United States.

In the period between 1990 and 2020, use of RH became a common cattle management strategy and therefore was added as an additional technology in the 2020 model that could not be reported in the 1990 model. Ractopamine hydrochloride compared with no technology increased final BW by 1.3%, increased ADG by 1.5%, and increased G:F by 2.7%. In addition, DP was increased when RH was fed compared to no technology (63.3 vs. 63.7%). When all 3 technologies were used in 2020, DMI increased slightly compared with no technology and ADG was improved by 24.1%, resulting in a 22.7% increase in G:F, which decreased DOF by 3 d. The DP of cattle administered all technologies increased by 1.0% compared with no technology. The improvements in growth performance and feed efficiency associated with the use of all technologies decreased enteric CH_4 (g/d) by 3.0% and liters per kilogram of DMI by 3.9% compared with no technology. In addition, use of all technologies in 2020 decreased N excretion per animal by 1.6%. MacDonald et al. (2009) indicated that use of implants, monensin, and a β-agonist decreased estimated enteric methane per animal by 7.6% and manure nitrogen of cattle by 5.7% when fed a 12.0% forage and 12.5% CP diet for 150 d. The greater difference observed by MacDonald et al. (2009) may be caused by greater DMI (9.36 kg). These data indicate sustainability of feedlot cattle production has improved through the use of technologies by decreasing the outputs that contribute to GWP.

Effects of the Overall Production System on Cattle Growth and Emissions (1990 vs. 2020)

Because of the differences in management practices and available technologies incorporated into the cattle management system from 1990 to 2020, direct comparisons of production outcomes between 1990 and 2020 should be interpreted with caution. However, the use of all technologies (implant and monensin in 1990 and implant, monensin, and RH in 2020) best represents the practices used on the majority of feedlots and should be representative of the cattle fed in each time period. Therefore, comparisons between 1990 and 2020 will only describe the combination of all available technologies within each year. From 1990 (Table 2) to 2020 (Table 3), the initial BW, final BW, and HCW increased by 7.5, 22.4, and 24.3% respectively. In addition to the increase in final BW, ADG increased from 1.48 to 1.65 kg/d, with an increase in DMI from 8.55 to 8.98 kg. This resulted in an 8.2% increase in G:F. Although a greater ADG was demonstrated in 2020 compared with 1990, the number of DOF was increased by 44 d to achieve the 95.0 kg of additional BW gain produced in 2020.

Daily enteric CH_4 production was less for cattle in feedlots in 1990 (79.49 g/d) compared with 2020 (84.85 g/d) because of less DMI in 1990. Reporting CH_4 as a proportion of DMI removes differences in intake and represents how diets affect CH_4 emissions. When CH_4 is expressed as liters per kilogram of DMI to account for differences in DMI, the cattle fed in 2020 produced slightly more CH_4 per kilogram of DMI than cattle in 1990 (13.20 vs. 12.72 L/kg of DMI) because the 2020 diet had greater calculated gross energy (NASEM, 2016) than the 1990 diet. Additionally, total fat and NDF concentrations in the diet increased from 1990 to 2020. It has been documented that increasing the dietary fat concentration can reduce CH_4 production (NASEM, 2016; Drehmel et al., 2018). However, increased NDF concentrations can increase CH_4 production (Hales et al., 2014). The equations used in this model for enteric CH_4 production (Powers et al., 2014) did not account for differences in dietary analysis. Total N intake throughout the feeding period was greater in 2020 (39.66 kg per animal) compared with 1990 (23.57 kg per animal), thus resulting in greater total N excretion in 2020 compared with 1990 (35.59 vs. 20.25 kg per animal). The greater N intake in 2020 versus 1990 is because of the greater dietary CP as a result of inclusion of byproducts in the 2020 diet. The increased DOF and daily DMI, and the inclusion of WDGS, resulted in a 36.4% increase in total manure DM output per animal across the feeding period and 36.5% increase in as-is total manure per animal.

Table 4. Carbon footprint [kg of CO_2 equivalents (CO_2e) per animal] of feedlot cattle finished using different technologies available in 1990

Item	No technology	Imp[1]	Mon[2]	Imp and Mon
Animal and manure				
Enteric CH_4	277.30	294.49	250.43	268.27
Manure N_2O	122.51	128.35	114.03	120.68
Manure CH_4	18.50	19.65	17.38	18.61
Indirect N_2O	22.69	24.10	21.31	22.83
Crop production				
Corn	349.02	370.65	327.80	351.16
Alfalfa hay	30.46	32.34	28.60	30.64
Soybean meal	26.94	28.61	25.30	27.11
Other	30.17	32.04	28.34	30.36
Transport				
Feed	42.17	44.79	39.61	42.43
Manure	1.23	1.31	1.16	1.24
Grain processing energy				
Natural gas	26.85	28.51	25.22	27.01
Electricity	14.77	15.68	13.87	14.86
Total production				
Total CO_2e	962.61	1,020.52	893.04	955.21
kg of CO_2e/kg of HCW[3]	3.05	3.03	2.83	2.83
kg of CO_2e/kg of BW gain	5.83	5.10	5.41	4.78
Total reactive N				
kg/animal	15.54	16.50	14.59	15.63
g/kg of HCW	49.20	48.94	46.20	46.37
g/kg of BW gain	94.17	82.48	88.43	78.14

[1]Cattle received a growth-promoting implant that contained estradiol twice during the finishing period.

[2]Cattle received monensin.

[3]HCW = hot carcass weight.

Technology Effects on Total Carbon Footprint

Because CH_4 and other greenhouse gas emissions have different impacts on the environment, it is important to convert them to a CO_2e basis. All emissions sources in 1990 (Table 4) and in 2020 (Table 5) increased when implants were used because of increased DMI. The increased DMI is supported by the equations established by Fox et al. (1992) indicating hormonal implants containing estrogenic compounds increase DMI. Therefore, in 1990 and 2020, implants increased total CO_2e per animal by 6.0 and 5.0%, respectively. Although total emissions were increased with the use of implants, when expressed per unit of BW gain, implants decreased kilograms of CO_2e per kilogram of BW gain by 0.73 kg in 1990 and 0.64 kg in 2020. Because DP was decreased in 1990 and increased in 2020 for implants, the decrease in kilograms of CO_2e per kilogram of HCW was 0.6 and 2.8% in 1990 and 2020, respectively. Stackhouse et al. (2012) calculated that steers that received an implant in both the stocker and feedlot system had reduced CO_2e per animal compared with cattle raised using a natural program that did not administer implants over their entire lifetime.

As described previously, monensin decreased DMI and slightly increased ADG in both 1990 and 2020 compared with no technology. The increased ADG with no change in final BW resulted in 3 and 1 less DOF in 1990 and 2020, respectively. The decreased DMI and fewer DOF associated with monensin decreased the amount of CO_2e from all sources, resulting in a reduction of total kilograms of CO_2e per animal by 7.8% in 1990 and by 4.5% in 2020. The proportional decrease is the same when expressed as kilograms of CO_2e per kilogram of BW gain when monensin is used because monensin did not increase the amount of BW gain during the feeding period.

When implants and monensin were fed in combination in 1990, all emissions were either decreased or similar when compared with the no technology group when expressed per animal and per kilogram of BW gain. In 2020 all emissions decreased per animal and resulted in total emissions decreasing when expressed as kilograms of CO_2e per animal compared with no technology. When implants

Table 5. Carbon footprint [kg of CO_2 equivalents (CO_2e) per animal for the entire feeding period] of feedlot cattle finished using different technologies available in 2020

Item	No technology	Imp[1]	Mon[2]	Imp and Mon	RH[3]	Imp, Mon, and RH
Animal and manure						
Enteric CH_4	397.50	417.22	369.85	379.72	406.33	379.72
Manure N_2O	215.39	226.33	208.58	212.50	221.20	212.09
Manure CH_4	25.55	26.82	24.73	25.39	26.12	25.39
Indirect N_2O	38.66	40.58	37.41	38.41	39.52	38.41
Crop production						
Corn	412.68	433.15	399.33	409.99	421.84	409.99
Alfalfa hay	29.12	30.57	28.18	28.93	29.77	28.93
Wet distillers grains plus solubles[4]	106.79	112.08	103.33	106.09	109.16	106.09
Other	41.68	43.75	40.33	41.41	42.60	41.41
Transport						
Feed	58.70	61.61	56.80	58.31	60.00	58.31
Manure	1.70	1.79	1.65	1.69	1.74	1.69
Grain processing energy						
Natural gas	31.74	33.32	30.72	31.54	32.45	31.54
Electricity	17.46	18.33	16.89	17.35	17.85	17.35
Total production						
Total CO_2e	1,376.99	1,445.55	1,317.81	1,351.33	1,408.58	1,350.92
kg of CO_2e/kg of HCW[5]	3.61	3.51	3.46	3.28	3.63	3.22
kg of CO_2e/kg of BW gain	5.68	5.04	5.45	4.72	5.65	4.58
Total reactive N						
kg/animal	26.49	27.80	25.63	26.31	27.08	26.31
g/kg of HCW	69.44	67.55	67.26	63.93	69.77	62.77
g/kg of BW gain	109.32	97.01	106.05	91.81	108.54	89.19

[1]Cattle received a growth-promoting implant that contained trenbolone acetate and estradiol twice during the finishing period.

[2]Cattle received monensin.

[3]Cattle received ractopamine hydrochloride in the last 28 d of feeding.

[4]For carbon footprint of wet distillers grains plus solubles, 50% was applied to the ethanol industry and 50% to the wet distillers grains plus solubles.

[5]HCW = hot carcass weight.

and monensin were used in combination, the kilograms of CO_2e per kilogram of BW gain was decreased from the no technology group by 22.0% in 1990 and by 20.3% in 2020. This indicates that in addition to the overall decrease in emissions when monensin and implants are used together, more BW gain is also obtained. Therefore, as cattle growth becomes more efficient, environmental impact decreases. The addition of RH in the 2020 model had little effect on kilograms of CO_2e per animal because RH had no effect on DMI or DOF. However, because RH increases ADG with no effect on DMI or DOF, an additional decrease in kilograms of CO_2e per kilogram of BW gain is captured. Thus, when all technologies were used in 2020, the kilograms of CO_2e per kilogram of BW gain was decreased by 24.0% compared with no technology. Because the only available technologies in 1990 were monensin and implants, the 22.0% decrease in CO_2e per kilogram of BW gain stated previously represents the effects of all technologies used in 1990. According to the IPCC (2006), growth technologies such as hormonal implants and ionophores have a technical reduction potential in North America of 9.0%, which is one of the largest reduction potentials in the world. The use of all available technologies in 1990 and 2020 reduced kilograms of CO_2e per kilogram of HCW by 7.8 and 12.1%, respectively. In addition, the use of growth-promoting technologies in 2020 has had a larger effects on the CO_2e per kilogram of BW gain in 2020 than in 1990 when compared with the use of no technologies in each year.

Effects of the Overall Production System on Total Carbon Footprint (1990 vs. 2020)

Overall, sources of emissions that have GWP from cattle and manure increased from 1990 (Table 4) to 2020 (Table 5) when expressed on a CO_2e per animal basis and was caused by the 44 additional DOF and greater DMI in 2020. Corn grain in 1990 produced 351.16 kg of CO_2e per animal and by 2020 increased by 16.8% to 409.99 kg of CO_2e per animal. The decrease in inclusion rate of corn from 76.4 to 65.4% likely helped to offset the increased DMI and longer DOF that caused an increase in the C-footprint associated with growing corn. Soybean meal was removed from the diet from 1990 to 2020, thus eliminating its contribution. However, WDGS were added as a byproduct feed in the time between 1990 and 2020 and contribute 106.09 kg of CO_2e per animal. Therefore, total crop production contribution of CO_2e per animal increased from 439.27 kg in 1990 to 586.42 kg in 2020. If expressed on a basis of CO_2e/100 kg of feed DM, in 1990 feed production contributed 37.27 CO_2e/100 kg of feed DM and in 2020 contributed 36.48 CO_2e/100 kg of feed DM (data not shown), indicating the effect of feed production has decreased. In addition, the proportion of total CO_2e associated with feed has decreased from 46.0% (Table 6) to 43.4% (Table 7) but still has the greatest effect on the overall C-footprint.

The CO_2e per animal of feed transport to the feedlot has increased from 42.43 to 58.31 kg from 1990 to 2020 because animals are fed for an additional 44 DOF. Similarly, manure transport away from the feedlot increased from 1.24 to 1.69 kg of CO_2e per animal because of the greater amount of manure produced, which is a result of the increased DOF in the 2020 model. The effects of natural gas and electricity required to steam flake corn has also increased from 1990 (27.01 and 14.86 kg of CO_2e per animal, respectively) to 2020 (31.54 and 17.35 kg of CO_2e per animal, respectively) because of the increase in dietary DMI per animal that was achieved from an increase in DOF. Although corn inclusion decreased from 1990 to 2020, total corn consumption per animal increased by 150.80 kg when comparing the all technology groups.

Overall, cattle in 1990 produced 955.21 kg of CO_2e per animal compared with 1,350.92 kg of CO_2e per animal in 2020. These values are similar to those reported for California beef production by Stackhouse-Lawson et al. (2012). However, it is important to note these values are not scaled to the quantity of HCW produced. When using all available technologies, in 1990 cattle produced 2.83 kg of CO_2e/kg of HCW compared with 3.22 kg of CO_2e/kg of HCW in 2020. Because initial BW did not increase to the same extent as HCW (7.5 vs. 24.3%), there is a disproportionate amount of additional BW gain required in 2020 compared with 1990 within the feedlot. Therefore, to compare more evenly across year, C-footprint can also be expressed per unit of BW gain. The feedlot contributed 4.78 kg of CO_2e/kg of BW gain in 1990, and in 2020 that was

Table 6. Carbon footprint (% of total carbon footprint) of feedlot cattle depending on technology use in 1990

Item	No technology	Imp[1]	Mon[2]	Imp and Mon
Animal and manure				
Enteric CH_4	28.81	28.86	28.04	28.09
Manure N_2O	12.73	12.58	12.77	12.63
Manure CH_4	1.92	1.93	1.95	1.95
Indirect N_2O	2.36	2.36	2.39	2.39
Feed production				
Corn	36.26	36.32	36.71	36.76
Alfalfa hay	3.16	3.17	3.20	3.21
Soybean meal	2.80	2.80	2.83	2.84
Other	3.13	3.14	3.17	3.18
Transport				
Feed	4.38	4.39	4.44	4.44
Manure	0.128	0.128	0.130	0.130
Grain processing energy				
Natural gas	2.79	2.79	2.82	2.83
Electricity	1.53	1.54	1.55	1.56
Summary				
Enteric	28.81	28.86	28.04	28.09
Manure	17.01	16.86	17.10	16.97
Feed production	45.35	45.43	45.92	45.99
Transport	4.51	4.52	4.56	4.57
Grain processing	4.32	4.33	4.38	4.38

[1]Cattle received a growth-promoting implant that contained estradiol twice during the finishing period.

[2]Cattle received monensin.

decreased by 4.4% to 4.58 kg of CO_2e/kg of BW gain. The reduction in CO_2e per kilogram of BW gain is supported by the IPCC (2014) indication that global kilograms of CO_2e per kilogram of beef has reduced from 1960 to 2010 by about 1.0 kg. It is not surprising that the IPCC (2014) has a slightly greater reduction in CO_2e per kilogram than the present study, because it incorporates all segments of the beef production system. In addition, there were fewer growth-promoting technologies available in 1960, causing the decrease from 1960 to 2010 to be more pronounced than that reported in the current model.

Although it is outside the scope of this study, it should be noted that overall cattle age at slaughter has decreased between 2001 and 2016 despite greater DOF (Lawrence et al., 2001; Eastwood et al., 2017). Dentition analysis is the most accurate demonstration of the reduction in animal age. The earliest record of dentition data in the United States was in 2001 (Lawrence et al., 2001), where it was observed that 75.4% of cattle had no permanent incisors at slaughter. More recently, in the 2016 National Beef Quality Audit, Eastwood et al. (2017) reported that 80.5% of cattle had no permanent incisors at slaughter. As such, if cattle are slaughtered at a younger age, total C-footprint per animal will likely be reduced over the total cattle life cycle.

Furthermore, as cattle spend more time in the feedlot, the amount of time spent in the cow-calf and stocker segments of the beef industry are reduced as a proportion of their total life. According to Stackhouse-Lawson et al. (2012), the feedlot produced 3.1 and 1.56 times less CO_2e per kilogram of BW gain than the cow-calf and stocker operations, respectively. Cattle spent 212 d in the cow-calf phase, 182 d in the stocker phase, and 121 d in the feedlot. Stackhouse-Lawson et al. (2012) indicated that if the stocker operation was removed, there is a potential decrease in total CO_2e of 6.5% over the entire beef production system. In addition, more growth-promoting technologies can be applied in the feedlot compared with the cow-calf operation, allowing for greater reductions in CO_2e.

When this model is extrapolated to the 33.24 million cattle slaughtered in 1990 (USDA-ERS, 2020), feedlots produced a total of 29.88 billion kilograms of CO_2e in 1990. In contrast, in 2020, 1.4% fewer cattle (USDA-ERS, 2020) were slaughtered but produced a total of 43.16 billion kilograms of CO_2e. As cattle spend a greater pro-

Table 7. Carbon footprint (% of total carbon footprint) of feedlot cattle depending on technology use in 2020

Item	No technology	Imp[1]	Mon[2]	Imp and Mon	RH[3]	Imp, Mon, and RH
Animal and manure						
Enteric CH_4	28.87	28.86	28.07	28.10	28.85	28.11
Manure N_2O	15.64	15.66	15.83	15.73	15.70	15.70
Manure CH_4	1.86	1.86	1.88	1.88	1.85	1.88
Indirect N_2O	2.81	2.81	2.84	2.84	2.81	2.84
Feed production						
Corn	29.97	29.96	30.30	30.34	29.95	30.35
Alfalfa hay	2.12	2.11	2.14	2.14	2.11	2.14
Wet distillers grains plus solubles[4]	7.76	7.75	7.84	7.85	7.75	7.85
Other	3.03	3.03	3.06	3.06	3.02	3.07
Transport						
Feed	4.26	4.26	4.31	4.32	4.26	4.32
Manure	0.124	0.124	0.125	0.125	0.124	0.125
Grain processing energy						
Natural gas	2.31	2.30	2.33	2.33	2.30	2.33
Electricity	1.27	1.27	1.28	1.28	1.27	1.28
Summary						
Enteric	28.87	28.86	28.07	28.10	28.85	28.11
Manure	20.31	20.32	20.54	20.45	20.36	20.42
Feed production	42.87	42.86	43.34	43.40	42.84	43.41
Transport	4.39	4.39	4.44	4.44	4.38	4.44
Grain processing	3.57	3.57	3.61	3.62	3.57	3.62

[1]Cattle received a growth-promoting implant that contained trenbolone acetate and estradiol twice during the finishing period.

[2]Cattle received monensin.

[3]Cattle received ractopamine hydrochloride the last 28 d of feeding.

[4]For carbon footprint of wet distillers grains with solubles, 50% was applied to the ethanol industry and 50% to the wet distillers grains plus solubles.

portion of their life in the feedlot, more of their lifetime emissions will be assigned to that segment of the industry. However, because cattle produced in 2020 had 47.5% more BW gain and 24.3% more HCW, the feedlot segment has reduced the quantity of emissions that contribute to GWP compared with the amount of beef produced, as evidenced by a 4.4% decrease in CO_2e per kilogram of BW gain.

APPLICATIONS

Based on the estimates reported in this study, incorporating the use of growth-promoting technologies into the beef feedlot production system improves performance of finishing cattle. Although concerns regarding the use of products such as implants, ionophores, and βAA have become prevalent in recent years, previous research indicates that these conventional management practices improve feedlot cattle production (Maxwell et al., 2014) and decrease the environmental impact (Stackhouse et al., 2012). The present study also suggests that these management strategies decrease the C-footprint of beef feedlots. From 1990 to 2020 feedlots have increased BW gain more than the increase in kilograms of CO_2e, resulting in a 4.4% decrease of CO_2e per kilogram of BW gain. The disproportionate increase in BW gain compared with CO_2e indicates that feedlots are decreasing the environmental impact intensity and improving efficiency, while continuing to meet the protein needs of a growing population. Therefore, current management practices that include the use of growth-promoting technologies in combination with improved production practices have increased performance of beef cattle, reduced the environmental impact per kilogram of BW gain, and positively affected the sustainability of beef production over the past 30 yr.

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