Effects of replacing corn with sorghum on the performance of overfed mule ducks

J. Arroyo, J. P. Dubois, F. Lavigne, Mathilde Brachet, Laurence Fortun-Lamothe

Effects of replacing corn with sorghum on the performance of overfed mule ducks

J. Arroyo,* J. P. Dubois,* F. Lavigne,* M. Brachet,†,‡,§ and L. Fortun-Lamothe†,‡,§,1

**ASSELDOR, the Goose and Duck Breeding Station, La Tour de Glane, 24420 Coulaures, France; †University of Toulouse INPT ENSAT, UMR1388 Physiology Genetics and Breeding Systems, F-31326 Castanet-Tolosan Cedex, France; ‡INRA, UMR1388 Physiology Genetics and Breeding Systems, F-31326 Castanet-Tolosan, France; and §University of Toulouse INPT ENVT, UMR1388 Physiology Genetics and Breeding Systems, F-31076 Toulouse, France*

ABSTRACT The aim of this trial was to study the effects of replacing yellow corn (C) with condensed tannin-free sorghum (S) during the finishing period (F period; age 53 to 79 d) and/or overfeeding period (O period; age 80 to 91 d) on the performance of overfed mule ducks. 192 ducks were divided into 4 groups (48 in each) differing in the cereal (yellow corn or sorghum) included in the diet given during the F and/or the O periods, using a 2 × 2 factorial arrangement of treatments : SS, SC, CS, CC. At the end of the O period, the birds were slaughtered after 10 h of fasting to measure *foie gras* and *magret* qualities. Mortality (1%; $P >$ 0.05) and weight gain (2,030 g; $P > 0.05$) during the O period were similar in the 4 groups. At the end of the O period, birds overfed with sorghum had *foie gras* that was heavier (723 *vs.* 694 g in CS+SS vs. CC+SC, respectively; $P < 0.05$) and less yellow (24.40 vs. 38.59 for b* in CS+SS vs. CC+SC, respectively; $P < 0.001$) than birds overfed with corn. Fat loss during *foie gras* cooking was similar in the 4 groups (18%; $P > 0.05$), but the *foie gras* was less yellow in birds overfed with sorghum (14.84 vs. 26.01 for b* in CS+SS vs. CC+SC, respectively; $P < 0.001$). Weight of *magret* was similar in the 4 groups (491 g, $P > 0.05$) but the color of the breast muscle and skin of *magret* was less yellow in birds overfed with sorghum compared with corn (12.26 vs. 12.92 and 13.84 vs. 18.30 in CS+SS vs. CC+SC, respectively; $P < 0.001$). In conclusion, the replacement of yellow corn with sorghum during finishing and/or overfeeding is possible and useful in a mule duck *foie gras* production system because it increases *foie gras* weight without decreasing the weight of *magret*. However, it changes the quality of the products, mainly their color.

Key words: mule ducks, sorghum, yellow corn, *foie gras*, overfeeding

2016 Poultry Science 00:1–8
http://dx.doi.org/10.3382/ps/pew072

INTRODUCTION

Eco-design processes are needed to improve the sustainability of livestock production systems and reduce their environmental impacts, while maintaining or increasing their economic viability and social acceptability, including product quality that meets consumer demand (Arroyo et al., 2013a). Feed is the main driver of environmental costs in poultry rearing (Boggia et al., 2010; Leinonen et al., 2012a, b). Feed formulation aims to meet the nutritional needs of the animals, taking into account the availability, price and nutrient content of the raw materials. However, it can also take into account new issues such as the environment (Nguyen et al., 2012; Arroyo et al., 2013d; Pomar et al., 2014).

In the French *foie gras* production system (duck and goose), corn is the main cereal used in the diet (Guémené and Guy, 2004), particularly during the overfeeding period, due to its high energy content in starch, which favors hepatic steatosis (Hermier et al., 1999). Sorghum (*Sorghum bicolor* (L.) Moench) could offer a useful alternative to corn, with both environmental and economic advantages. Its nutritional characteristics are similar to those of corn (Sauvant et al., 2004), but it is more drought-resistant (Farré and Faci, 2006). It could therefore reduce the vulnerability of crops to water shortage, and need less irrigation. It could also improve the flexibility of production systems, reducing their reliance on raw materials whose prices fluctuate widely.

Recently Arroyo et al. (2013b) showed that replacing corn with sorghum in goose feeding during the finishing (**F**) and overfeeding (**O**) periods resulted in an increased weight of *foie gras,* but with no effect on bird mortality. By contrast, corn replacement with sorghum during only the F period increased mortality during the

Received November 13, 2015.
Accepted January 15, 2016.
[1]Corresponding author: lamothe@toulouse.inra.fr

O period. Such a result was explained by the need for the digestive tract of geese to adapt to a new diet differing both in particle size and composition.

Some data are available for the use of sorghum in duck feed (Elkin et al., 1990, 1991). However, none of the studies was done using overfed duck, even though 95% of the *foie gras* production in France comes from ducks. Furthermore, in the last decade, *magret* (pectoral muscle with skin of overfed duck; JORF, 1986), a co-product of *foie gras*, has experienced a sharp increase in consumer demand.

The aim of this work was to study the effects of replacing yellow corn with sorghum during the F and/or the O periods on the performance of overfed mule ducks and the quality of products. This quality was principally assessed by commercial grading after evisceration—appearance such as color and fat loss after cooking for the *foie gras* (Théron et al., 2013), and by the quantity of meat and its color for the *magret* (Baéza et al., 2013a).

MATERIALS AND METHODS

The present study complied with the French National Regulations for human care and use of animals for research purposes. The ducks were bred at the Goose and Duck Breeding Station (Coulaures, Dordogne, France), which has experimental approval A24-137-1 and technical staff and scientists with individual authorizations to conduct animal experimentation in accordance with good animal practice issued by the DDCSPP (Directorate Departmental of Social Cohesion and the protection of populations). In this experiment, all the birds were killed according to the European Council regulations (EC, 2009).

Birds and Experimental Design

Male mule ducks (*Cairina moschata* × *Anas platyrhynchos*) from the commercial line MMGAS × PKL were supplied by Orvia Ent. (Le Pin, Deux-Sèvres, France). The birds were divided into 4 groups differing in the cereal included in the diet given during the F period (2 levels: yellow corn: **C**, or condensed tannin-free sorghum: **S**) and in the cereal included in the diet given during the O period (2 levels: yellow corn or condensed tannin-free sorghum), in a 2 × 2 factorial arrangement of treatments (CC, CS, SC, SS). The sorghum produced in France is actually considered as condensed tannin-free (Conan et al., 1992).

A total of 800 birds were fed a prestarter mashed diet (AME_n 12.3 MJ/kg, CP 220 g/kg) from age one to 13 d, a starter pelleted diet (AME_n 11.7 MJ/kg, CP 180 g/kg) from age 14 to 30 d, and a grower pelleted diet (AME_n 12.1 MJ/kg, CP 16.5%) from age 31 to 52 d. From age 53 to 79 d (F period) the birds were fed a pelleted diet containing 500 g of sorghum/kg (SS and SC groups; n = 400) or 500 g of yellow corn/kg (CS and CC groups; n = 400). These 2 experimental diets were isocaloric and isonitrogenous (AME_n 12.1 MJ/kg, CP 152 g/kg). Briefly, all the feedstuffs were ground before being mixed and then pelleted. Steam was added during the pelleting process. At the end, the average length and diameter of the pellets were 9.5 mm and 4.2 mm, respectively. The feed was manufactured by the Sud-Ouest Aliment society (Haut-Mauco, Landes, France).

From age 80 d to 90 d (O period), 192 birds (n = 96 by F diet) chosen according to their BW at 79 d, were fed a wet mash containing cereal (30% whole grain and 70% ground grain): 971 g of yellow corn/kg (SC and CC; AME_n 18.6 MJ/kg, CP 73 g/kg) or 965 g of sorghum/kg (SS and CS; AME_n 18.6 MJ/kg, CP 100 g/kg), water (670 or 780 g/kg in the corn and sorghum diet, respectively), and vitamin-mineral complex. The amount of water added was higher in the sorghum than in the corn diet to permit easy overfeeding of birds in each group despite the lower water-holding capacity of sorghum compared with corn (Arroyo et al., 2012a; Brachet et al., 2015). The diets used during the rearing period and the cereal included in the overfeeding mixture were supplied by Sud-Ouest Aliment (Haut-Mauco, Landes, France). The composition of the 4 experimental diets is shown in Table 1.

Housing and Management Conditions

From age one to 79 d, the 800 birds were housed in 2 pens of 150 m^2. Room temperature was maintained at 28°C from the first wk after hatching, and was then gradually reduced to 20°C at age 28 d, after which no heating was provided, and ducks had outdoor access between 07:00 and 18:00 from age 28 d to 79 d. From 56 d to 79 d, outdoor access was denied while the birds received experimental diets, and so the time of outdoor access was reduced (09:00 to 18:00). The feeders were managed to prepare the birds for overfeeding (Guéméné and Guy, 2004) as previously described by Arroyo et al. (2014).

At 80 d, the 192 male mule ducks (48 ducks per treatment), chosen according their BW at 79 d, were divided into 24 pens (3 × 1 m for eight ducks). The room was maintained at a temperature of <20°C and a relative humidity of <90%. The planned overfeeding program (Figure 1) was adapted from Arroyo et al. (2014). Specifically, whichever cereal was used in the mixture, the ducks were overfed once a d at 80 d, twice a day from d 81 to d 87, and 3 times a day from d 88 to d 90. Generally, ducks are overfed twice a day during the O period (Guéméné and Guy, 2004), but in this experiment, the volume of the mixture was greater when it contained sorghum than when it contained corn, due to the higher swelling capacity of sorghum. In compliance with animal welfare, ducks were therefore overfed 3 times a day at the end of the O period, as is done with geese (Arroyo et al., 2012b), to give a smaller volume each time, without changing daily intake.

Table 1. Ingredients and chemical composition of the experimental diets.

	Finishing diet		Overfeeding diet	
	Corn	Sorghum	Corn	Sorghum
Ingredients (g/kg)				
Corn	50.00	3.00	971.0[1]	–
Sorghum	–	50.02	–	964.9[1]
Wheat	15.55	16.35	–	–
Sunflower cake	10.00	10.00	–	–
Defatted rapeseed meal	9.90	5.90	–	–
Corn distillers	10.00	10.00	–	–
Beet molasses	2.00	2.00	–	–
Calcium carbonate	1.40	1.45	–	–
Dicalcium phosphate	0.35	0.38	–	–
Sodium chloride	0.20	0.19	–	–
L-Lysine-HCl	0.20	0.26	–	–
DL-Methionine	0.14	0.19	–	–
Choline chloride	0.04	0.04	–	–
Ronozyme NP®,[2]	0.01	0.01	–	–
Ronozyme WX®,[3]	0.01	0.01	–	–
Vitamin and premix	0.20[4]	0.20[4]	29.0[5]	35.1[5]
Nutrient levels[6] (% of raw material)				
DM[7]	87.6	85.0	87.0	87.2
Ash[8]	4.8	4.7	1.7	1.5
CP[9]	15.2	15.2	7.3	10.0
Cellulose[10]	5.6	5.2	3.0	3.4
Fat[11]	3.5	3.4	3.6	3.3
Starch[12]	43.4	46.2	48.9	48.3
Methionine + Cystine[13]	0.8	0.8	0.2	0.2
Lysine[13]	0.7	0.7	0.3	0.3
Threonine[13]	0.6	0.5	0.5	0.2
AME_n, MJ/kg	12.1	12.1	18.6	18.6

[1]300 g/kg as whole grain and 700 g/kg as ground meal. [2]Ronozyme NP® made by DSM (JH Heerlen, The Netherlands). [3]Ronozyme WX® made by DSM (JH Heerlen, The Netherlands). [4]Vitamin for finishing diet: Vitamin A: 3,750 IU/kg; vitamin D3 15,000 IU/kg [5]Vitamin and mineral premix for overfeeding diet: (A: 180,000 IU/kg; D3: 50,000 IU/kg; E: 2,250 IU/kg; B1: 100 mg/kg; K3: 200 mg/kg; CON: 1,170 mg/kg) and mineral premix [$CuSO_4$: 667 mg/kg; ZnO: 3,600 mg/kg; $SeSO_4$: 74.00 mg; Na^2SeO^3: 13.5 mg/kg; clay (bentonite): 580 g/kg] manufactured by Sanders (Chateau-Gontier, Mayenne, France). [6]3 replicates by analyses; [7]AFNOR (Association Française de normalisation), 1982; [8]AFNOR, 1977; [9]AFNOR, 1997b; [10]AFNOR, 1993a; [11]AFNOR, 1997a; [12]Ewers, 1972; [13]AFNOR 1993b.

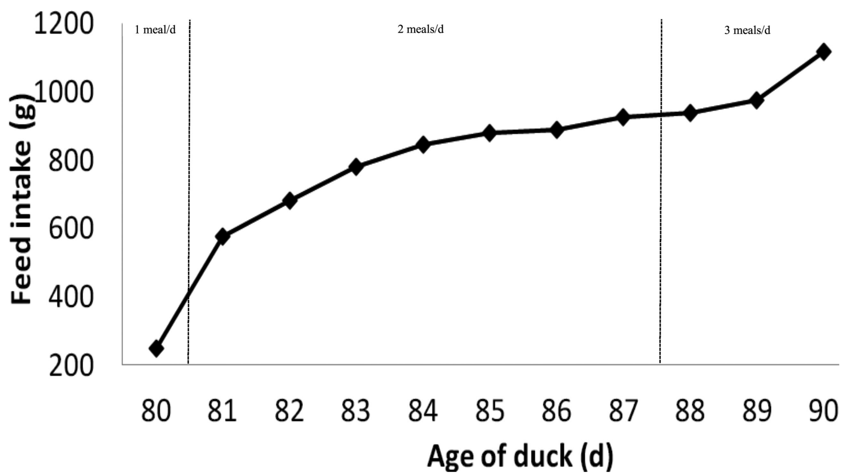

Figure 1. Planned cereal intake (without water) of birds during the overfeeding period.

Measurements and Analyses

Diets The chemical composition of the experimental diets was analyzed by INRA (Toulouse, France) and is shown in Table 1. Particle size was measured using successive sieves of decreasing mesh size on the wet material for the pelleted diets given during the finishing period (Lebas and Lamboley, 1999), or on the dry material for the diet given during the overfeeding period (Melcion, 2000).

Animals Birds were weighed individually at 53 d, 79 d, and 80 d after 18 h of fasting and at 91 d after 10 h of fasting. *Foie gras* exhibited marked weight loss during fasting, and at the end of the O period, fasting should not exceed 12 h to preserve *foie gras* weight and quality. The actual quantity of feed given to the birds during the O period was measured individually for each meal. Mortality was recorded daily throughout the experiment.

At 79 d, 14 birds per group, chosen according to their BW, were slaughtered to study gizzard, gut, and liver development and carcass traits by the WPSA method (Fris Jensen, 1984). The weights of the gut (small intestine, duodenum, jejunum, ileum, and cecum), gizzard, liver, carcass (eviscerated carcass with skin), and abdominal fat were measured together with breast and thigh weights (without skin and subcutaneous fat).

Foie gras and Magret Birds were slaughtered after 10 h of fasting. Carcasses were eviscerated 20 min postmortem, after scalding and plucking. Muscle was sampled as described by Arroyo et al. (2012a). The entire right *magret* was cut according to commercial standards, and the breast muscle and skin were weighed. The color was then measured on the muscle and skin using the trichromatic CIE Lab coordinates system (L^*, a^*, b^*), using a CR 300 Minolta chromameter (Minolta, Osaka, Japan).

After carcass evisceration, the liver was removed and weighed. Color was measured in the cold (4°C) *foie gras* along the ventral face of the large lobe (CR 300 Minolta chromameter, Minolta, Osaka, Japan). The average of 3 measurements at different sites (top, middle, and bottom of the large lobe) was computed for each liver. Commercial grading was carried out by a specialist from the industry blind to the treatments (Cooperative Sarlat Périgord, Sarlat-la-Canéja, Dordogne, France), and trained to classify raw *foie gras* according to its potential commercial use. The livers were graded on a 3-point scale. The first point of the scale designated fatty livers with no defects, appropriate texture, normally used for processing as entire canned livers and had the highest commercial value. The second point of the scale designated livers with no defects but that were too heavy to process as whole canned livers, and the third point of the scale designated livers with numerous defects, either in terms of appearance or texture, with a lower commercial value.

After color measurement and commercial grading, the livers were prepared for cooking. The main blood vessels were carefully removed, and a slice weighing 180 ± 5 g was excised perpendicularly to the long axis of the liver and across the large and small lobes. This sample was placed in a glass container. Salt (12 g/kg of liver) and pepper (3 g/kg of liver) were added, and each container was closed and cooked for 1 h in water at 85°C, under a pressure of 0.8 bar. After chilling for 30 min, the containers were removed from the autoclave and stored at +4°C. After 2 months of storage, the containers were opened and the visible fat was removed. The amount of fat lost during cooking was expressed as a percentage of the initial liver weight. After this process, the liver was cut perpendicularly to the long axis of the liver position in the container, and the color was immediately measured along the face of the cut (CR 300 Minolta chromameter, Minolta, Osaka, Japan).

Table 2. Granulometric characteristics of the experimental diets.

Particle mesh size (mm)	Finishing diet[1] Corn %	Finishing diet[1] Sorghum %	Overfeeding diet[2] Corn %	Overfeeding diet[2] Sorghum %
4	0.00	0.00	29.63	0.00
3	0.00	0.00	0.34	27.38
2	0.00	0.00	0.43	2.22
1	51.32	69.76	15.72	11.40
0.5	21.95	16.36	28.76	30.52
0.315	10.94	6.22	12.32	9.33
<0.315	15.79	7.66	12.80	19.15

[1]Particle size was measured using successive sieves of decreasing mesh on the wet material for the pelleted diets given during the finishing period (Lebas and Lamboley, 1999) with 3 samples per diet.

[2] Particle size was measured using successive sieves of decreasing mesh on the dry material for the diet given during the overfeeding period (Melcion, 2000) with 3 samples per diet.

Statistical Analysis

Data were analyzed with the GLM procedure using the PASW Statistics18 package program for Windows (PASW Statistics18, 2010, SPSS Inc., Chicago, IL). For all data, the individual duck was used as the experimental unit. The data were subjected to a 2-way ANOVA. In a first analysis, the effect of pens and its interaction with cereal were also included in the model. However, they were not significant and were removed from the final model (data not shown).

Treatment means were compared using Duncan's multiple range test. The particle size distribution of the diets, commercial grading, and bird mortality during overfeeding periods were analyzed using the χ^2 test. Differences were treated as significant when $P \leq 0.05$.

RESULTS

Physical Characteristics of the Experimental Diets

The physical characteristics of the experimental diets are shown in Table 2. The particle size distribution was similar in the 2 diets given during the F period ($P > 0.05$). Conversely, the proportion of large particles (>4 mm) was higher in the corn-based overfeeding diet than in the sorghum-based one (29.6% *vs.* 0.0%; $P < 0.001$) because corn grains are larger (>4 mm) than sorghum seeds (2 to 4 mm). However, the proportion of medium-sized particles (2 to 4 mm) was lower in the corn- than in the sorghum-based diet given during the O period (0.8 vs. 29.6%; $P < 0.001$). The proportion of small particles (<1 mm) was similar in both diets (69.6% vs. 67.4%; $P > 0.05$; Table 2).

Bird Performance

During the F period, the BW at 53 d and 79 d were similar whatever the F diet (3529 g, $P = 0.083$ and 4510 g, $P = 0.988$, respectively). Between 53 d and 79 d, the

Table 3. Performance of ducks during the finishing period (age 53 to 79 d).

	Group[1]			P^2
Item	CC + CS	SC + SS	SEM	F
BW[3] (g)				
at 53 d	3544	3514	8.6	0.083
at 79 d	4511	4510	11.2	0.988
ADG (g/d)				
53 to 79 d	40	41	0.4	0.346
FCR[4]	7.31	7.11	0.060	0.089
53 to 79 d				
Carcass composition at 79 d (n = 14 /group)				
BW (g)	4526	4502	51.7	0.819
Carcass (g)	2854	2837	39.8	0.827
Liver (% of BW)	1.60	1.60	0.032	0.989
Gizzard (% of BW)	1.99	2.12	0.046	0.172
Gut (% of BW)	3.31[b]	3.61[a]	0.069	0.024
Abdominal fat (% of BW)	1.40	1.51	0.077	0.474
Pectoral muscle (% of carcass)	11.12	10.99	0.117	0.590
Skin of pectoral muscle (% of carcass)	2.93	2.85	0.076	0.648
Thigh with bones[5] (% of carcass)	9.21	9.04	0.087	0.328

[1]CC: corn during finishing period and corn during overfeeding period; CS: corn during finishing period and sorghum during overfeeding period; SC: sorghum during finishing period and corn during overfeeding period; SS: sorghum during finishing period and sorghum during overfeeding period.

[2]F: Finishing period.

[3]400 birds/group.

[4]FCR: feed conversion ratio per bird was determined using measured live weight (individual measure) and estimated feed intake (measure per pen[6]).

[5]Without skin and subcutaneous fat.

[6]Feed intake during 53 to 79 d was 6,761 g/bird in SC+SS, and 6,750 g/bird in CS+CC.

SEM: standard error of the mean.

[a,b]Within a row, means with no common superscript differed at $P < 0.05$.

ADG and the FCR were also similar between SC+SS and CS+CC (40 g/d, $P = 0.346$ and 7.21, $P = 0.089$, respectively, Table 3). At 79 d, except for the relative weight of the gut, which was lower in birds fed corn instead of sorghum (−8%, $P = 0.024$), the other body traits were similar between the 2 groups ($P > 0.05$, Table 3).

No interaction between the effect of cereal given during the F and O periods was significant concerning the performance of ducks (Table 4). The bird mortality was similar among the 4 groups during the O period (1%, $P > 0.05$, Table 4). The BW was similar among the 4 groups at 80 d (4519 g, $P > 0.05$; Table 4). The birds had similar average gain (2,030 g, $P > 0.05$), feed conversion ratio (4.50; $P > 0.05$), and BW at 91 d (6549 g, $P > 0.05$; Table 3) in the 4 groups despite higher feed intake for birds overfed with sorghum (+0.25% g/duck in CS+SS *vs.* CC+SC; $P < 0.01$; Table 4).

Magret and Foie Gras Quality

Foie gras was heavier (723 vs. 694 g, in CS+SS vs. CC+SC, respectively; $P < 0.05$) and less yellow (24.40 vs. 38.59 for b^*, in CS+SS vs. CC+SC, respectively; $P < 0.001$) in birds overfed with sorghum than with corn. Conversely, the cereal given during the F or O periods had no effect on L^* or a^* values (Table 5). This modification in the yellow color reduced the commercial grading of the *foie gras* from birds overfed with sorghum (20 vs. 53% in class 1 and 73 vs. 44% in class 2, in CS+SS vs. CC+SC, respectively; $P < 0.001$). The interaction between the 2 periods was also significant for *foie gras* commercial grading, SC having a higher percentage of *foie gras* in class 1 than the other 3 groups (66% *vs.* 27%; $P < 0.001$; Table 5).

The weight of *magret* was similar in the 4 groups (491 g; $P > 0.05$) and the weight of breast muscle was similar (318 g; $P > 0.05$) among the 4 groups, but breast muscle had lower values for yellowness (12.26 vs. 12.92 of b^*; $P < 0.01$) in birds overfed with sorghum than with corn. The cereal given during the F or O periods had no effect on the other color values (Table 5).

The skin of *magret* was lighter (177 vs. 171 g; $P < 0.05$), less yellow (18.31 vs. 13.84 for b^*; $P < 0.01$), and with lower lightness (77.13 vs. 78.11 for L^*; $P < 0.01$) in birds overfed with sorghum than with corn. Birds fed with sorghum during the F period also had a yellower skin on *magret* (16.77 vs. 13.84; $P < 0.01$) than birds fed with corn (Table 5).

The fat loss during cooking was similar in the 4 groups (18%; $P > 0.05$), but birds overfed with sorghum had less yellow *foie gras* (14.84 *vs.* 26.01 for b^*, in CS+SS vs. CC+SC, respectively; $P < 0.001$), while the cereal given during the F and O periods had no effect on the other color values (Table 6).

DISCUSSION

The objective of this work was to study the effects of replacing yellow corn with sorghum during

Table 4. Performance of ducks during the overfeeding period (age 80 to 91 d).

	Group[1]					P^2		
Item[2]	CC	CS	SC	SS	SEM	F	O	F*O
Mortality	0/48	0/48	1/48	1/48		0.147	0.773	0.568
BW at 80 d (g)	4528	4525	4517	4507	20.3	0.718	0.880	0.931
Feed intake (g)	8844	8874	8844	8859	3.8	0.313	0.003	0.313
Average gain (g)	2030	2045	2005	2039	13.0	0.559	0.351	0.721
Feed conversion ratio	4.38	4.39	4.43	4.38	0.03	0.756	0.720	0.547
BW at 91 d (g)	6558	6570	6522	6546	21.3	0.484	0.671	0.893

[1]CC: corn during finishing period and corn during overfeeding period; CS: corn during finishing period and sorghum during overfeeding period; SC: sorghum during finishing period and corn during overfeeding period; SS: sorghum during finishing period and sorghum during overfeeding period; [2]F: Finishing period; O: Overfeeding period.

[2]48 ducks/group.

SEM: standard error of the mean.

Table 5. Effects of replacing corn with sorghum on the quality of products from overfed ducks before cooking.

	Group[1]					P^2		
Item	CC	CS	SC	SS	SEM	F	O	F*O
Number of samples	48	48	47	47				
Foie gras								
Foie gras weight (g)	710	722	678	723	7.6	0.267	0.039	0.239
Foie gras color								
L*	71.52	71.60	70.84	70.81	0.201	0.069	0.942	0.897
a*	12.41	12.08	12.76	12.67	0.136	0.082	0.440	0.655
b*	38.56	24.60	38.62	24.21	0.591	0.656	<0.001	0.542
Commercial grading (%)								
1	40.0	20.0	66.7	19.5				
2	60.0	72.5	28.2	73.2		0.153	<0.001	<0.001
3	0.0	7.5	5.1	7.3				
Magret								
Weight	492	488	497	487	2.9	0.660	0.224	0.614
Breast muscle weight (g)	317	318	319	316	2.2	0.981	0.832	0.640
Pectoral muscle color								
L*	47.24	47.48	46.96	47.19	0.170	0.415	0.494	0.995
a*	24.26	24.13	24.52	24.13	0.081	0.439	0.104	0.411
b*	12.93	12.28	12.91	12.24	0.102	0.873	0.001	0.953
Skin of *magret* weight (g)	175	170	178	171	1.5	0.406	0.039	0.779
Skin of *magret* color								
L*	77.60	78.15	76.65	78.07	0.149	0.076	0.001	0.130
a*	1.13	1.43	1.40	1.98	0.122	0.090	0.069	0.550
b*	18.99	14.54	17.62	13.14	0.216	<0.001	<0.001	0.941

[1]CC: corn during finishing period and corn during overfeeding period; CS: corn during finishing period and sorghum during overfeeding period; SC: sorghum during finishing period and corn during overfeeding period; SS: sorghum during finishing period and sorghum during overfeeding period.

[2]F: Finishing period; O: Overfeeding period.

SEM: standard error of the mean.

F and/or O periods on performance of overfed mule ducks. The results showed that the use of sorghum, during the F and O periods or O period only, improved *foie gras* weight without modifying the feed conversion ratio or the weight of *magret*, but it affected the *magret* and *foie gras* quality, mainly decreasing the yellowness and reducing the commercial grading of *foie gras*.

In geese, switching the cereal included in the diet between the F and O periods reduced the performance of the geese, mainly increasing mortality (Arroyo et al., 2013b). This result suggests that the digestive tract of birds needs first to adapt to the diet using during the O period. In the present study, no such effect was observed. This suggests that mule ducks are hardier than geese and able to adapt quickly to changes in environmental conditions (Guy et al., 1995).

The higher *foie gras* weight in birds overfed with sorghum agrees with results of Arroyo et al. (2013b) in geese. This result can be explained by a higher protein content in sorghum than corn (+2.7 pt/kg; + 37%) as previously shown in geese (Nir et al., 1972, 1973; Arroyo et al., 2013b, 2013c). Additionally, the amylopectin/amylose ratio in starch is generally higher in sorghum than in corn (Jenkins and Donald, 1995), and amylopectin is more digestible than amylose (Zhou et al., 2010). The influence of fasting duration on yield has previously been shown in broilers (Kim et al., 2007). In *foie gras* production, when fasting is prolonged the energy balance becomes negative, and

Table 6. Effects of replacing corn with sorghum on the quality of products of overfed duck after cooking (n = 40 samples/group).

Item	Group[1]				SEM	P^2		
	CC	CS	SC	SS		F	O	F*O
Foie gras								
Fat loss during cooking (%)	20.56	18.65	14.26	19.74	1.019	0.200	0.378	0.070
Trichromatic coordinate at glass container opening								
L*	67.69	69.12	67.53	67.83	0.267	0.172	0.103	0.284
a*	5.91	6.50	6.51	6.38	0.137	0.385	0.394	0.186
b*	26.16	14.98	25.95	14.70	0.498	0.579	<0.001	0.939

[1]CC: corn during finishing period and corn during overfeeding period; CS: corn during finishing period and sorghum during overfeeding period; SC: sorghum during finishing period and corn during overfeeding period; SS: sorghum during finishing period and sorghum during overfeeding period.
[2]F: Finishing period; O: Overfeeding period.
SEM: standard error of the mean.

hepatic metabolism switches to lipolysis and energy utilization (Baéza et al., 2013b).

The weight of *magret* was similar, whichever cereal was included in the diet during the finishing and overfeeding period. Hence the higher protein content in sorghum than in corn had no positive effect on muscle development. Similar results were previously shown in geese (Arroyo et al., 2013b). It is known that the development of *magret* mainly occurs in early age. Higher weights of *magret* have been obtained by increasing the protein dietary content (22 vs. 19 g CP/kg) during the first 6 wk of age (Auvergne et al., 2013). Whereas the *foie gras* characteristics depended mainly on the diet given during the O period, present results confirm that the composition of the diet offered during the rearing period mainly influenced the *magret* quality.

The different size of food particles between overfeeding diets can also partly explain the heavier *foie gras* in birds overfed with sorghum, as previously shown in geese (Arroyo et al., 2013b; 2013c). Particle size influences the size of the gizzard (Carré, 2000), and the gizzard is an essential contributor to gastrointestinal motility (Duke, 1982, 1992) and digestive efficiency that in turn can affect the time of fasting before slaughter.

The lower yellowness in the *magret* and *foie gras* of birds fed sorghum can be explained by the lower carotenoid and vitamin A content in sorghum compared with corn (Sauvant et al., 2004). A similar effect was previously observed in the skin of broilers and in egg yolk (Gualtieri and Rapaccini, 1990), meat of broilers (Garcia et al., 2013), Japanese quail egg yolks (Freitas et al., 2014), and goose *foie gras* (Arroyo et al., 2013b). In the present study, flavor and texture of products were not explored. However, Arroyo et al. (2013a) showed in geese consumers' acceptability of *magret* and *foie gras* from geese fed with sorghum was reduced (intension of reuptake the product 52 vs. 69%) not due to a change in flavor or texture but due only to the lower yellowness of the products.

In conclusion, these results show a significant effect of replacing yellow corn with sorghum during finishing and overfeeding periods on the performance of overfed mule ducks. Replacing yellow corn with sorghum during finishing and overfeeding periods increased the weight of *foie gras* with no detrimental effect on bird mortality or weight of *magret*. However, it modified the sensory quality of the products, mainly reducing yellowness. The possibility of using sorghum in duck diet, especially during the overfeeding period, could widen the range of raw materials usable for *foie gras* production and so improve the flexibility of this farming system by making it less dependent on corn availability and market prices. However, the consequences of such feeding practice on the environmental impact of mule duck *foie gras* production needs further study.

ACKNOWLEDGMENTS

The authors thank the staff of the Goose and Duck Breeding Station (Dordogne, France) for their excellent supervision of this study and the staff of the UMR1388 Génétique Physiologie et Systèmes d'Elevage especially, C. Bannelier and C. Pautot for technical assistance in the analysis of samples. The authors acknowledge also the Interprofession Foie Gras (CIFOG), French national found (CASDAR n° 5328), the Aquitaine regional and Dordogne departmental councils for funding the project.

REFERENCES

AFNOR. 1977. Aliments des animaux. Dosage des cendres brutes. NF V 18–101, Association Française Normalisation, Paris. France.

AFNOR. 1982. Aliments des animaux. Détermination de la teneur en eau. NF V 18–109, Association Française Normalisation, Paris, France.

AFNOR. 1993a. Aliments des animaux. Détermination de la cellulose brute NF V03–040, Association Française Normalisation, Paris, France.

AFNOR. 1993b. Aliments des animaux. Dosage des acides aminés. NF V18–113, Association Française Normalisation, Paris, France.

AFNOR. 1997a. Aliments des animaux. Dosage de la matière grasse. NF V 18–117, Association Française Normalisation, Paris, France.

AFNOR. 1997b. Aliments des animaux. Dosage de l'azote, méthode par combustion (DUMAS). NF V 18–120, Association Française Normalisation, Paris, France.

Arroyo, J., A. Auvergne, J. P. Dubois, F. Lavigne, M. Bijja, C. Bannelier, and L. Fortun-Lamothe. 2012a. Effects of presentation and type of cereals (corn or sorghum) on performance of geese. Poult. Sci. 91:2063–2071.

Arroyo, J., L. Fortun-Lamothe, J. P. Dubois, F. Lavigne, and A. Auvergne. 2012b. Schedule and management of food transitions in geese for the production of *foie gras*. INRA Prod. Anim. 25:419–430.

Arroyo, J., J. Aubin, A. Auvergne, J. P. Dubois, X. Fernandez, M. Brachet, P. Debaeke, and L. Fortun-Lamothe. 2013a. Design and evaluation of an innovative foie gras production system: substitution of corn by sorghum in geese as an example. INRA Prod. Anim. 26:435–448.

Arroyo, J., A. Auvergne, J. P. Dubois, F. Lavigne, M. Bijja, C. Bannelier, H. Manse, and L. Fortun-Lamothe. 2013b. Effects of substituting yellow corn for sorghum in geese diets on *magret* and *foie gras* quality. Poult. Sci. 92:2448–2456.

Arroyo, J., A. Auvergne, J. P. Dubois, F. Lavigne, M. Bijja, and L. Fortun-Lamothe. 2013c. Influence of amount and form of sorghum in the diet on the performance of overfed geese. J. Appl. Poult. Res. 22:849–854.

Arroyo, J., L. Fortun-Lamothe, A. Auvergne, J. P. Dubois, F. Lavigne, M. Bijja, and J. Aubin. 2013d. Environmental influence of maize substitution by sorghum and diet presentation on goose foie gras production. J. Clean. Prod. 59:51–62.

Arroyo, J., L. Fortun-Lamothe, J. P. Dubois, F. Lavigne, M. Bijja, and C. Molette. 2014. The influence of choice feeding and cereal type (corn or triticale) during the finishing period on performance of mule ducks. Poult. Sci. 93:2220–2226.

Auvergne, A., J. Arroyo, M. Bijja, F. Lavigne, and J. P. Dubois. 2013. Interest of phase-feeding to geese rearing and force-feeding. In Proc. 10$^{\text{èmes}}$ Journées de la Recherché Avicole et Palmipèdes à Foie Gras. La Rochelle, France. 881–885.

Baéza, E., X. Fernandez, and C. Marie-Etancelin. 2013a. Carcass and meat quality of overfed waterfowl. INRA Prod. Anim. 26:425–434.

Baéza, E., C. Marie-Etancelin, S. Davail, and C. Diot. 2013b. Hepatic steatosis in waterfowl. INRA Prod. Anim. 26:403–414.

Boggia, A., L. Paolotti, and C. Castellini. 2010. Environmental impact evaluation of conventional, organic and organic-plus poultry production systems using life cycle assessment. World's Poult. Sci. J. 66:95–114.

Brachet, M., J. Arroyo, A. Cazals, C. Bannelier, and L. Fortun-Lamothe. 2015. Hydration capacity: a new criterion for feed formulation. Anim. Feed Sci. Technol. 209:174–185.

Carré, B. 2000. Effects of feed particle size on the digestive processes in domestic birds. INRA Prod. Anim. 13:131–136.

Conan, L., J. P. Métayer, M. Lessire, and J. L. Widiez. 1992. Metabolizable energy content of cereal grains in poultry. Recent yearly surveys in France. INRA Prod. Anim. 5:329–338.

Duke, G. E. 1982. Gastrointestinal motility and its regulation. Poult. Sci. 61:1245–1256.

Duke, G. E. 1992. Recent studies on regulation of gastric motility in turkeys. Poult. Sci. 71:1–8.

Elkin, R. G., J. C. Rogler, and T. W. Sullivan. 1990. Comparative effects of dietary tannins in ducks, chicks, and rats. Poult. Sci. 69:1685–1693.

Elkin, R. G., J. C. Rogler, and T. W. Sullivan. 1991. Differential response of ducks and chicks to dietary sorghum tannins. J. Sci. Food Agr. 57:543–553.

European Union Council Directive 1009/2009/EC. 2009. On the protection of animals at the time of slaughter or killing. Official Journal of European Community L. 303:1–30.

Ewers, E. 1972. Dosage de l'amidon par la méthode polarimétrique. J. O. CEE. 15:7–9.

Farré, I., and J. M. Faci. 2006. Comparative response of maize (*Zea mays L.)* and sorghum (*Sorghum bicolor L. Moench*) to deficit irrigation in a Mediterranean environment. Agric. Water Manage. 83:135–144.

Freitas, E. R., D. L. Raquel, A. J. N. Nascimento, P. H. Watanabe, and I. R. V. Lopes. 2014. Complete replacement of corn by white or red sorghum in japanese quail feeds. Braz J. Poult. Sci. 16:333–336.

Fris Jensen, J. 1984. Working Group V: Method of dissection of broiler carcases and description of parts. Terms used for parts of poultry in different languages ed. World's Poultry Science Association, European Federation, Denmark.

Garcia, R. G., A. A. Mendes, I. C. L. Almeida Paz, C. M. Komiyama, F. R. Caldara, I. A. Nääs, and W. S. Mariano. 2013. Implications of the use of sorghum in broiler production. Braz J. Poult. Sci. 15:257–262.

Gualtieri, M., and S. Rapaccini. 1990. Sorghum grain in poultry feeding. World's Poult. Sci. J. 46:246–254.

Guémené, D., and G. Guy. 2004. The past, present and future of force-feeding and "foie gras" production. World's Poult. Sci. J. 60:210–222.

Guy, G., D. Rousselot-Pailley, and D. Gourichon. 1995. Comparison of geese, mule duck and muscovy duck after cramming. Ann. Zootech. 44:297–305.

Hermier, D., M. R. Salichon, G. Guy, R. Peresson, J. Mourot, and S. Lagarrigue. 1999. Hepatic steatosis in waterfowl: metabolic basis and genetic susceptibility. INRA Prod. Anim. 12:265–271.

Jenkins, P. J., and A. M. Donald. 1995. The influence of amylose on starch granule structure. Int. J. Biol. Macromol. 17:315–321.

JORF (Journal Officiel de la République Française). 1986. Décret n°86–226 du 18 Février 1986 relatif à la dénomination de 'magret' ou ' maigret '.

Kim, D. H., Y. M. Yoo, S. H. Kim, B. G. Jang, B. Y. Park, S. H. Cho, P. N. Seong, K. H. HahJ, M. Lee, Y. K. Kim, and I. H. Hwang. 2007. Effect of the length of feed withdrawal on weight loss, yield and meat color of broiler, Asian-Aust. J. Anim. Sci. 20:106–111.

Lebas, F., and B. Lamboley 1999. Liquid phase sifting determination of the size of particles contained in pelleted rabbits feeds. World Rabbit Sci. 7:229–235.

Leinonen, I., A. G. Williams, J. Wiseman, J. Guy, and I. Kyriazakis. 2012a. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems. Poult. Sci. 91:8–25.

Leinonen, I., A. G. Williams, J. Wiseman, J. Guy, and I. Kyriazakis. 2012b. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: egg production systems. Poult. Sci. 91:26–40.

Melcion, J. P. 2000. Feed particle distribution: measurement, techniques and applications. INRA Prod. Anim. 13:81–98.

Nguyen, T. T. H., I. Bouvarel, P. Ponchant, and H. M. G. van der Werf, 2012. Using environmental constraints to formulate low-impact poultry feeds. J. Clean. Prod. 28:215–224.

Nir, I., M. Perek, and Z. Katz. 1972. The influence of soybean meal supplemented to maize diet of forced-fed geese upon their liver, organ and blood plasma components. Ann. Biol. Anim. Bioch. Biophys. 12:77–89.

Nir, I., Z. Nitsan, and A. Vax. 1973. The influence of force feeding and of protein supplementation to the diet on the metabolisable energy diets, digestibility of nutrients, nitrogen retention and digestive enzymes output in geese. Ann. Biol. Anim. Bioch. Biophys 13:465–479.

Pomar, C., J. Pomar, F. Dubeau, E. Joannopoulos, and J. P. Dussault. 2014. The impact of daily multiphase feeding on animal performance, body composition, nitrogen and phosphorus excretions, and feed costs in growing–finishing pigs. Animal. 8:704–713.

Sauvant, D., J. M. Perez, and G. Tran. 2004. Tables of composition and nutritive value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses, fish. eds INRA Editions, Paris and Wageningen Academic Publishers, The Netherlands. 304 pp.

Théron, L., M. Bouillier-Oudot, C. Marie-Etancelin, C. Bonnefont, X. Fernandez, and C. Molette. 2013. Melting rate after cooking of fatty liver in waterfowl. INRA Prod. Anim. 26:415–424.

Zhou, Z., H. F. Wan, Y. Li, W. Chen, Z. L. Qi, P. Peng, and J. Peng. 2010. The influence of the amylopectin/amylose ratio in samples of corn on the true metabolizable energy value for ducks. Anim. Feed Sci. Technol. 157:99–103.