Production system based global livestock sector modeling: Good news for the future

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Paper prepared for presentation at the EAAE 2011 Congress
Change and Uncertainty
Challenges for Agriculture,
Food and Natural Resources

August 30 to September 2, 2011
ETH Zurich, Zurich, Switzerland

Abstract
Livestock is recognized as one of the major drivers of current and future global change. This is caused on the production side, by the substantial resource requirements (land and water) per unit of output, and the related greenhouse gas emissions, and on the consumption side, by the growing demand due to population and economic growth. Our paper investigates whether productivity gains which enabled to the crop sector to satisfy the increased demand under decreasing real prices, and with little additional land, in the past decades, can be expected in the livestock sector in the future.
To answer this question, we implement the recursively dynamic partial equilibrium bottom-up model of the global agriculture and forest sectors (GLOBIOM), expanded by a newly developed livestock module. The livestock module is based on the Sere and Steinfeld livestock production system classification, characterized by detailed input-output coefficients, including manure and greenhouse gas emissions.
Our results show that if the production system composition is allowed to freely adapt to economic and resource constraints, the increases in per hectare productivity will allow satisfying the 2030 demand for ruminant products with less land than in 2000, and the livestock product prices will remain stable. This contrasts with the numbers obtained, when the ruminant production system structure is kept constant as in 2000, resulting among others in three times higher carbon prices. The adaptation in the livestock sector is hence a condition for sustainable future development, and it has to be taken into account when designing future policies.

Keywords: mathematical programming, livestock, land use change

1. Introduction

According to FAO statistics (FAOSTAT) livestock occupies some 30% of the global land and it is still the major driver of land use change. Gibbs et al. (2010) found that 83% of agricultural land expansion in the tropics between 1980 and 2000 went into forests. Mainly in Latin America, a large share of this expansion can be allocated to pasture and soybean cultivation for livestock (Nepstad et al., 2006; Barona & et al., 2010). Hence, livestock is substantial contributor to climate change (FAO, 2006a) and biodiversity losses. Due to continued population and economic growth, the total demand for calories from animal origin is projected to double by 2050 (FAO, 2006b).

Satisfying the forecasted food demand within the business as usual production model seems to be infeasible. Many authors agree that either the consumption has to be reviewed down, or considerable productivity gains must be achieved. Large scale quantitative assessments of the effects on land use and greenhouse gas emissions of human diet changes towards less meat confirmed the expected benefits the consumption side can play (Stehfest et al., 2009; Popp et al., 2010). But if we look in the past, it was rather through productivity increases than reduced consumption that the equilibrium on agricultural markets arisen.

Productivity increases in the crop sector enabled over the past fifty years to reduce the real commodity prices, to save 85% of the cropland compared to a situation without productivity increases, and to avoid emissions of some 590 GtCO2-eq (Burney et al., 2010). There is clear evidence about past productivity increases in the livestock sector too (Steinfeld & Gerber, 2010; Thornton, 2010). Also a recent forward looking study carried out by Wirsenius et al. (2010) suggests that feasible livestock productivity increases may lead to land saving rather than expansion by 2050. However there is no unanimity. Pelletier & Tyedmers (2010) calculate that even widespread adoption of high productivity systems would not prevent livestock from approaching and even transgressing some of the "planetary boundaries of the safe operating space for humanity" (Rockstrom et al., 2009).

None of the above mentioned future productivity studies adopted an economic framework, and the productivity changes were always imposed exogenously. Here we present and implement a new version of the Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2010) to investigate what the future productivity gains and their policy implications could be, based on economic behavior and a detailed production system classification (Sere & Steinfeld, 1996). GLOBIOM is a bottom-up partial equilibrium model of the global agriculture and forest sectors. While global in coverage, it is based on a detailed spatial resolution for its production parameters. It has been used in the past for global integrated assessments with focus on future land and water requirements (Schneider et al., 2011; Smith et al., 2010).

The use of the Sere and Steinfeld livestock production system classification in forward-looking global land use models was pioneered by Bouwman et al. (2005) who implemented a version aggregated into two production systems (pastoral and mixed (crop-livestock)/landless in the IMAGE model. Within their approach, the link to an economic model was only indirect, and the changes in the composition of the livestock sector in terms of production systems were exogenously determined. Hence, the major innovation of the approach presented here is that it allows for endogenous shifts in the production system composition in response to future economic drivers and physical constraints.

The application presented here investigates two alternative scenarios: one where the production system structure in the ruminant sector is allowed to freely adapt to the future conditions, and another one where it is fixed to the composition observed in 2000; the second case mimics livestock representation by country level averages. We hope that these scenarios are useful both to illustrate how a detailed modeling of the livestock sector may change the obtained results, and to show the importance of this adaptation flexibility for sustainable future development.

The rest of the paper is structured in a stylized way: Section 2 presents the innovative features of our model, Section 3 gives the main results of the explored scenarios, and Section 4 concludes with some discussion.

2. Methods

The analysis is carried out using the Global Biosphere Management Model (GLOBIOM)[1] (Havlík et al., 2010). GLOBIOM is a global recursive dynamic partial equilibrium bottom-up model integrating the agriculture and forestry sectors with the aim to give policy advice on global issues concerning land use competition between the major land-based production sectors. Economic concept and structure of GLOBIOM are similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider et al., 2007).

In GLOBIOM, the world is divided into 28 economic regions representing either individual large countries or aggregates of countries. Demand and international trade are represented at the level of these regions. The supply side of the model is based on a detailed disaggregation of land into Simulation Units – clusters of 5 arcmin pixels belonging to the same country, altitude, slope and soil class, and to the same 30 arcmin pixel (Skalský et al., 2008). Crop, forest and short rotation coppice productivity is estimated together with related environmental parameters like greenhouse gas budgets or nitrogen leaching, at the level of Simulation Units, either by means of process based biophysical models, e.g. Environmental Policy Integrated Climate Model EPIC (Williams, 1995), or by means of downscaling (Kindermann et al., 2008). Changes in the demand on the one side, and profitability of the different land based activities on the other side, are the major determinants of land use change in GLOBIOM.

The model allows for endogenous change in land use within the available land resources, where the total land area is fixed over the simulation horizon. Land use change possibilities are limited in basically two ways: (1) through explicit constraints on conversion from one land use to another and (2) by linking land suitability criteria to

[1] www.globiom.org

production potentials. For details on suitability analysis, the reader is referred to (Havlík et al., 2010), where also all basic assumptions are presented in detail.

The major innovative feature of the applied GLOBIOM version is that its livestock sector representation is fully consistent with the ILRI/FAO production systems classification (http://www.fao.org/AG/againfo/resources/en/glw/GLW_prod-sys.html - updated (Sere & Steinfeld, 1996)). For ruminants we consider four production systems: grassland based, mixed, urban and other. The first two systems are further differentiated by agro-ecological zones; for our classification we retained the three zones arid/semi-arid, humid/subhumid, temperate/tropical highlands. Monogastrics are split in Industrial and Other systems. For poultry, we assume specialized production of laying hens or broilers in the industrial systems, while a mix of the two is considered for the Other system. Eight different animal groups are considered: bovine dairy and meat herds, sheep and goat dairy and meat herds, poultry broilers, poultry laying hens, mixed poultry, and pigs. The ruminant dairy herds are further refined into adult dairy females and replacement heifers, which differ in feed requirements.

Detailed feed ratios for ruminants were calculated based on the RUMINANT model (Herrero et al., 2008). Simpler feed ratios were designed for monogastrics based on literature review and consultancy with CGIAR experts. Energy requirements of monogastrics in industrial systems are supposed to be fully satisfied by commercially produced concentrates. In Other/smallholder monogastric systems, only a share of the energy requirements is satisfied from concentrates, the rest is supposed to be complemented by scavenging and other occasional feed sources. In order to mimic the scarcity of these non-commercial feedstuffs, we keep the numbers of animals in the Other monogastric systems constant over the simulation horizon. Hence the share of the production from the non-industrial systems decreases over time.[2]

Diets estimated through the RUMINANT model are in the first step defined in terms of: grazing, concentrates, stover, and occasional. In the second step, the concentrates item is further decomposed to 10 finer feedstuff groups respecting, on the one hand, the biological constraints, and on the other hand FAOSTAT numbers on feed consumption.

Animal numbers in GLOBIOM are at the country level compatible with FAOSTAT, and they are further downscaled to the Simulation Unit level on the basis of updated (Kruska et al., 2003) animal densities and production system distribution maps. Grazing requirements are to be satisfied at the level of Simulation Unit, since we do not expect much trading in the grass. Stover balance is controlled at the country level, and feedstuff constituting the concentrates is balanced at the regional level. Since concentrates are to a large extent composed from crops, also interregional trade is possible.

Productivity is another output parameter of the RUMINANT model. Hence it is species, production system and region specific. In total, we represent in GLOBIOM 6 products: milk, bovine meat, sheep and goat meat, pork, poultry meat, and eggs.

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[2] Similar assumption was made by Keyzer et al. (2005).

Beyond the input-output coefficients which enable us to parameterize the Leontieff production functions of GLOBIOM, RUMINANT provides also corresponding methane emissions from enteric fermentation and N-excretion. The latter one is then converted to the N2O emissions using the IPCC tiers 2 methodology, and production system specific emission coefficients.

3. Scenarios and results

Our forward looking scenarios are in general driven mainly by the population and economic growth, technological change, and forecasted demand for bioenergies. Here we investigate the future developments up to 2030. The baseline scenario adopted assumes that by 2030, the population increased by 36% compared to 2000, the per capita income increased by 90%, the first generation biofuel consumption is up by about 400%, and the second generation biofuels, inexistent in 2000, are in 2030 slightly more important than the first generation.

Two alternative pathways are explored: DETAILED – ruminant production systems are represented in the full resolution, and the model is free to adapt the production system composition to the future drivers and constraints; AVERAGED – we still keep the detailed representation, but force the livestock system composition at the country level to remain as in the base year, which mimics the case where the ruminant production were represented through a single aggregated production system corresponding to the country level average.

Main results with respect to the development of the global ruminant sector are presented in Table 1 (Regionally disaggregated results are available in Table A1, in the Appendix). The simulations indicate a 51% growth in the supply of ruminant proteins over the period 2000-2030 if we consider the AVERAGED scenario. If the systems are allowed to adapt, the supply of proteins will be by further 6% higher. The higher production is obtained with only about 10% more animals compared to 2000. Although the production is higher in the DETAILED scenario, it is achieved by 3% less animals compared to the AVERAGED scenario. Such a result is allowed by 46% and 36% gains in aggregate productivity per animal in the DETAILED and AVERAGED scenarios, respectively.

From the sustainability perspective, it is more important to look at the land intensity of the production, in terms of land area mobilized for production of a given amount of output. According to our calculations, grassland area used for ruminant production was in 2000 more than 20 times larger than the cropland area. In the AVERAGED scenario, cropland area utilized for ruminant production increases over the entire simulation horizon by 2% only, and the grassland area increases by 8%. In the DETAILED scenario, shifts in the production systems lead to an increased demand for cropland, by 24%, but the necessary grassland area decreases by 2.5%. This leads in the sum to a decrease in the absolute area in ruminant production by 1.3% compared to 2000, which is considerably different from the increase by 8% in the rigid AVERAGED scenario. (Similar conclusions were obtained by Wirsenius et al. (2010).)

Table 1. Global ruminant production characteristics by 2000 and 2030

		2000	2030	2030/2000
Production [1000 ton]	DETAILED	34306	55041	**60.4**
	AVERAGED	34306	51815	**51.0**
	DIFF [%]		**6.2**	
Stock [1000 TLU]	DETAILED	1145060	1255810	**9.7**
	AVERAGED	1145060	1291107	**12.8**
	DIFF [%]		**-2.7**	
Animal Productivity	*DETAILED*	*0.030*	*0.044*	***46.3***
[Ton of Protein / TLU]	*AVERAGED*	*0.030*	*0.040*	***34.0***
	DIFF [%]		***9***	
CrpLnd [1000 ha]	DETAILED	96726	120177	**24.2**
	AVERAGED	96726	98670	**2.0**
	DIFF [%]		**21.8**	
GrsLnd [1000 ha]	DETAILED	2089262	2036477	**-2.5**
	AVERAGED	2089262	2264116	**8.4**
	DIFF [%]		**-10.1**	
AllLnd [1000 ha]	DETAILED	2185988	2156654	**-1.3**
	AVERAGED	2185988	2362785	**8.1**
	DIFF [%]		**-8.7**	
Land Intensity	*DETAILED*	*64*	*39*	***-38.5***
[ha / ton of Protein]	*AVERAGED*	*64*	*46*	***-28.4***
	DIFF [%]		***-14***	

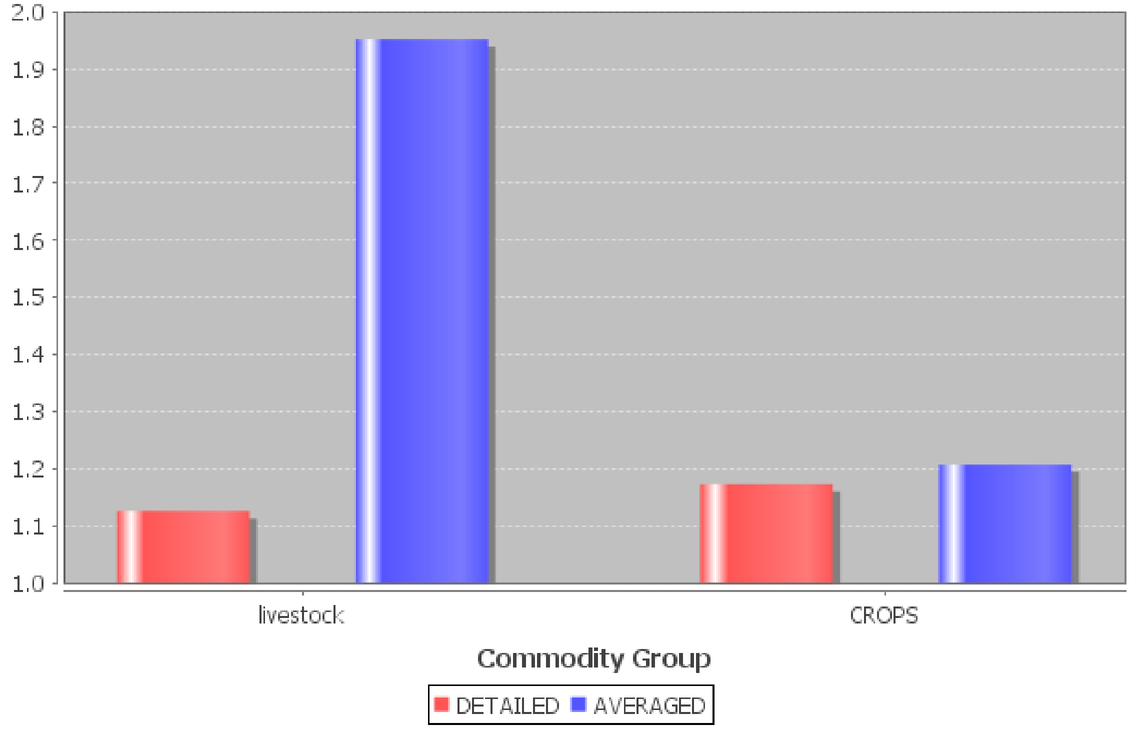
The differences in the structure of the global ruminant herd in terms of production systems according to the different scenarios are showed in Table 2, regional disaggregation is provided again in the Appendix, Table A2. The total ruminant number is in the DETAILED scenario by 3% lower than in the AVERAGE. There is a more than proportional decrease of animals in the extensive Grassland Based and Other systems. The animal numbers remain relatively stable in the Mixed Extensive systems. The highest increase in animal numbers is observed in the Mixed Intensive systems, closely followed by the Urban Systems.

Table 2. World ruminant numbers by production system in 2030 [1000 TLU]*

		AnySystem	GrasBased	MixedExt	MixedIn	OtherSys	UrbanSys
WRD	DETAILED	1255810	256912	456057	212100	182634	148108
	AVERAGED	1291107	300019	447103	146153	291834	105998
	DIFF [%]	**-2.7**	**-14.4**	**2.0**	**45.1**	**-37.4**	**39.7**

* For those familiar with the FAO/ILRI system classification, GrasBased covers LGA, LGH, LGT,LGHYP, MixedExt covers MRA, MRH, MRHYP, MIA, MIH, MIHYP, MixedInt covers MRT and MIT, and Other and Urban remain the same.

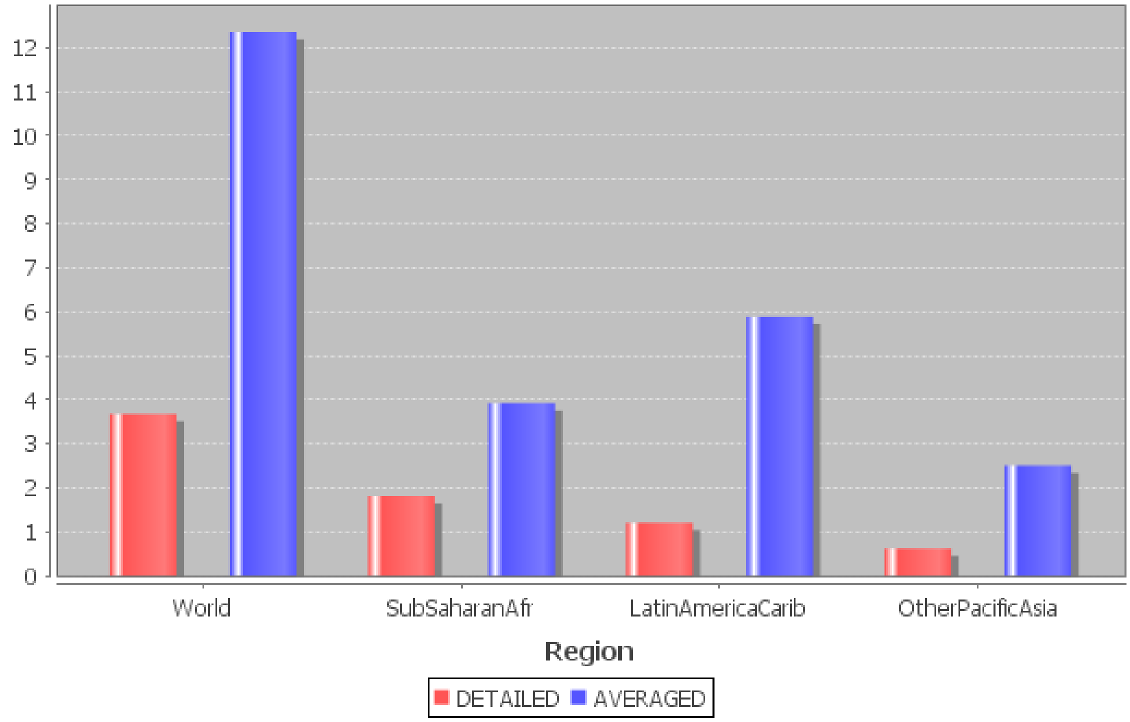
Figure 1. Commodity price indexes 2030 relative to 2000



The level of flexibility which we include into the ruminant systems has obviously also effect on many other model outputs. Figure 1 presents the different values of crop and livestock commodity price indexes, as the aggregate indicator of the overall economic impacts. While the crop price index comparing the prices in 2030 to 2000 is relatively stable across the scenarios, the global animal product prices would nearly double, if the 2000 ruminant production system structure should remain unchanged until 2030. This contrasts with the increase of some 12% only, if the systems are allowed to adapt.

Finally, we investigated the impacts of the different scenarios on the rates of deforestation. Deforestation is directly linked both to the climate change mitigation and biodiversity protection - the two hottest topics in the global environmental sustainability debate - and institutions like the European Commission or the World Wildlife Fund are considering ambitious targets on its reduction in the near future. In Figure 2, we show that the global rate of gross deforestation reaches some 12 million ha per year in the AVERAGED scenario (values close to those observed in the recent past), while it goes down to not even 4 million hectares if the ruminant system structure freely adapts. This has clear implications also for the design of policies for reduction of (emissions) from deforestation and their cost. While the price (calculated as a tax) of bringing emissions from gross deforestation to zero in 2030 reaches some 90 USD per ton of CO2 and hence makes this target realistic if evaluated through the DETAILED scenario, the price obtained under the AVERAGED scenario reaches nearly 300 USD, and hence is far above what the current expectations about the 2030 CO2 price are.

Figure 2. Annual rate of gross deforestation by 2030 [million ha per year]



4. Conclusion

This paper presented the new, production system based, livestock sector module implemented in the GLOBIOM model, and appraised the importance of such an approach in forward looking integrated assessments, both for the agricultural sector analysis, as well as for environmental policy design in areas of climate change and biodiversity protection.

Comparing two scenarios, one in which the ruminant production systems can freely adapt to future drivers and constraints, and another one where the production system structure is bounded to the structure observed in the base year, lead often to opposite results. For example, in one scenario the total land used for ruminant production in 2030 exceeds substantially the area used in 2000, in the other scenario the area required is lower. Similarly livestock product prices can, depending on the scenario/approach adopted, stay relatively stable or double already by 2030, the rates of deforestation can remain as in the past decades, our be three times lower. Overall, the results of the flexible production system based model provide substantially better news for the future than implementation of a rigid averaged structure, which would often lead to alarmist conclusions.

The obtained results can be viewed from two perspectives: *i)* importance of representing livestock sector flexibility in large scale economic models, *ii)* role the adaptation should play facing the future challenges. With respect to the first point we propose differentiated production system representation as the source of flexibility compared to implementation of average numbers, which does not allow for any endogenous adaptation. One could argue that production system based approach is not necessary to represent productivity changes. Especially computable general equilibrium models have plenty of experience in modeling endogenous productivity growth. But the current generation of these models unfortunately does not represent all the physical relationships involved in productivity increases, although we are aware about attempts to remedy on this point. Some other models, consider the productivity change as completely exogenous without any feedback on the feed demand, and hence may lead to overoptimistic conclusions.

With respect to the second point, it will be necessary to represent the flexibility only if the reality can really be flexible. In the presented scenarios, we assumed either a free adaptation of the production systems or their full rigidity. But since our framework does not explicitly account for e.g. capital accumulation, the switches between the systems may in reality be slower than what our results indicate. Beyond the economic constraints, there may be other infrastructural, physical and institutional, barriers to adaptation. The positive results linked to higher flexibility in our model, could be used by policy makers as an argument to facilitate this type of adaptation.

What we presented here is just a small step to correctly represent the livestock sector in global economic models. In the sustainability assessment, we did not address at all the social sustainability although the structural changes considered above may have far reaching impacts. Whether and where, they will be positive, as assumed by Herrero et al. (2010), or negative, remains to be assessed. Given the important role livestock sector plays in the global development, these challenges must be addressed in future research, to critically review our conclusions, and may be announce even some better news.

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APPENDIX

Table A1. Regional ruminant production characteristics by 2030

		WRD	EUR	FSU	LAM	MENA	NAM	OPA	PAC	PAO	SAS	SSA
Production	DETAILED	55041	10797	4596	5817	3579	5398	924	2968	2224	16207	2531
[1000 ton]	AVERAGED	51815	11114	4038	5695	2465	5234	1232	2517	2339	14755	2426
	DIFF [%]	**6.2**	**-2.8**	**13.8**	**2.1**	**45.1**	**3.1**	**-25.0**	**17.9**	**-4.9**	**9.8**	**4.3**
Stock	DETAILED	1255810	111392	60977	260374	49224	101500	56390	126968	53311	275413	160262
[1000 TLU]	AVERAGED	1291107	109883	47016	313289	47304	111621	66521	120115	52477	249675	173206
	DIFF [%]	**-2.7**	**1.4**	**29.7**	**-16.9**	**4.1**	**-9.1**	**-15.2**	**5.7**	**1.6**	**10.3**	**-7.5**
Animal Productivity	*DETAILED*	*0.044*	*0.097*	*0.075*	*0.022*	*0.073*	*0.053*	*0.016*	*0.023*	*0.042*	*0.059*	*0.016*
[Ton of Protein / TLU]	*AVERAGED*	*0.040*	*0.101*	*0.086*	*0.018*	*0.052*	*0.047*	*0.019*	*0.021*	*0.045*	*0.059*	*0.014*
CrpLnd [1000 ha]	DETAILED	120177	11621	12934	10740	14650	13292	3688	4169	3517	41734	3833
	AVERAGED	98670	11855	7359	5677	9872	13881	5685	3298	4370	32440	4233
	DIFF [%]	**21.8**	**-2.0**	**75.7**	**89.2**	**48.4**	**-4.2**	**-35.1**	**26.4**	**-19.5**	**28.7**	**-9.5**
GrsLnd [1000 ha]	DETAILED	2036477	47070	117405	271172	975706	109181	6335	23407	103272	14873	368056
	AVERAGED	2264116	49253	128544	382626	987650	124662	30502	24628	105349	21702	409198
	DIFF [%]	**-10.1**	**-4.4**	**-8.7**	**-29.1**	**-1.2**	**-12.4**	**-79.2**	**-5.0**	**-2.0**	**-31.5**	**-10.1**
AllLnd [1000 ha]	DETAILED	2156654	58691	130338	281912	990356	122473	10023	27576	106789	56607	371888
	AVERAGED	2362785	61108	135903	388303	997522	138544	36188	27926	109718	54142	413431
	DIFF [%]	**-8.7**	**-4.0**	**-4.1**	**-27.4**	**-0.7**	**-11.6**	**-72.3**	**-1.3**	**-2.7**	**4.6**	**-10.0**
Land Intensity	*DETAILED*	*39*	*5*	*28*	*48*	*277*	*23*	*11*	*9*	*48*	*3*	*147*
[ha / ton of Protein]	*AVERAGED*	*46*	*5*	*34*	*68*	*405*	*26*	*29*	*11*	*47*	*4*	*170*

(WRD – World, EUR – Europe, FSU – Former Soviet Union, LAM – Latin America, MENA – Mid East North Africa, NAM – North America, OPA – Other Pacific Asia, PAC – Planned Asia and China, PAO – Pacific OECD, SAS – South Asia, SSA – Sub-Saharan Africa)

Table A2. Regional ruminant numbers by production system in 2030 [1000 TLU]*

		AnySystem	GrasBased	MixedExt	MixedIn	OtherSys	UrbanSys
WRD	DETAILED	1255810	256912	456057	212100	182634	148108
	AVERAGED	1291107	300019	447103	146153	291834	105998
	DIFF [%]	**-2.7**	**-14.4**	**2.0**	**45.1**	**-37.4**	**39.7**
EUR	DETAILED	111392	33028	20042	34844	13315	10163
	AVERAGED	109883	28579	10664	26568	26708	17365
	DIFF [%]	**1.4**	**15.6**	**87.9**	**31.2**	**-50.1**	**-41.5**
FSU	DETAILED	60977	26413	5971	22566	4148	1879
	AVERAGED	47016	11505	2480	20648	10137	2246
	DIFF [%]	**29.7**	**129.6**	**140.7**	**9.3**	**-59.1**	**-16.3**
LAM	DETAILED	260374	24019	190648	16353	25563	3792
	AVERAGED	313289	72507	145632	9208	74730	11212
	DIFF [%]	**-16.9**	**-66.9**	**30.9**	**77.6**	**-65.8**	**-66.2**
MENA	DETAILED	49224	8948	13658	14837	982	10799
	AVERAGED	47304	16701	17769	2365	3065	7405
	DIFF [%]	**4.1**	**-46.4**	**-23.1**	**527.4**	**-68.0**	**45.8**
NAM	DETAILED	101500	49179	4877	9854	18161	19428
	AVERAGED	111621	36052	3143	28047	35618	8760
	DIFF [%]	**-9.1**	**36.4**	**55.2**	**-64.9**	**-49.0**	**121.8**
OPA	DETAILED	56390	18025	21036	8770	6458	2100
	AVERAGED	66521	2655	32527	1553	24993	4793
	DIFF [%]	**-15.2**	**578.9**	**-35.3**	**464.8**	**-74.2**	**-56.2**
PAC	DETAILED	126968	21877	39761	47619	14396	3315
	AVERAGED	120115	25483	20598	33028	32256	8750
	DIFF [%]	**5.7**	**-14.2**	**93.0**	**44.2**	**-55.4**	**-62.1**
PAO	DETAILED	53311	15758	22703	7511	4526	2813
	AVERAGED	52477	24416	11690	660	11147	4564
	DIFF [%]	**1.6**	**-35.5**	**94.2**	**1038.4**	**-59.4**	**-38.4**
SAS	DETAILED	275413	27946	67702	18355	72543	88866
	AVERAGED	249675	18208	127683	4767	60249	38767
	DIFF [%]	**10.3**	**53.5**	**-47.0**	**285.0**	**20.4**	**129.2**
SSA	DETAILED	160262	31718	69659	31390	22542	4953
	AVERAGED	173206	63913	74919	19309	12930	2134
	DIFF [%]	**-7.5**	**-50.4**	**-7.0**	**62.6**	**74.3**	**132.0**

(WRD – World, EUR – Europe, FSU – Former Soviet Union, LAM – Latin America, MENA – Mid East North Africa, NAM – North America, OPA – Other Pacific Asia, PAC – Planned Asia and China, PAO – Pacific OECD, SAS – South Asia, SSA – Sub-Saharan Africa)

* For those familiar with the FAO/ILRI system classification, GrasBased covers LGA, LGH, LGT,LGHYP, MixedExt covers MRA, MRH, MRHYP, MIA, MIH, MIHYP, MixedInt covers MRT and MIT, and Other and Urban remain the same.