

## ORIGINAL RESEARCH

# Assessment of driving factors for yield and productivity developments in crop and cattle production as key to increasing sustainable biomass potentials

Sarah Gerssen-Gondelach<sup>1</sup>, Birka Wicke<sup>1</sup> & Andre Faaij<sup>2</sup><sup>1</sup>Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands<sup>2</sup>Energy and Sustainability Research Institute, University of Groningen, Nijenborg 4, 9747 AC Groningen, The Netherlands**Keywords**

Biomass potential, cattle production, crop production, driving factors, sustainability, yield developments

**Correspondence**

Sarah Gerssen-Gondelach, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands.  
Tel: +31 30 253 5446;  
E-mail: s.j.gerssen-gondelach@uu.nl

**Funding Information**

This research was conducted within the research program "Knowledge Infrastructure for Sustainable Biomass", which is funded by the Dutch Ministries of 'Economic Affairs' and 'Infrastructure and the Environment'.

Received: 23 September 2014;

Revised: 2 March 2015;

Accepted: 10 March 2015

**Food and Energy Security 2015; 4(1): 36–75**

doi: 10.1002/fes3.53

**Abstract**

The sustainable production potential of biomass for energy and material purposes largely depends on the future availability of surplus agricultural lands made available through yield improvements in crop and livestock production. However, the rates at which yields may develop, and the influence of technological, economic and institutional factors on these growth rates are key uncertainties in assessing the potentials and impacts of biomass production. This study analyzes the pace and direction of historical yield developments (1961–2010) of five major crops, beef and cow milk in Australia, Brazil, China, India, USA, Zambia, and Zimbabwe, and examines the driving factors behind these developments. In addition, it explores how future yields are modeled and how modeling efforts may be improved. Average yield growth rates over the investigated period ranged in most cases between 0.7–1.6% year<sup>-1</sup> for crops, 1.0–1.5% year<sup>-1</sup> for milk, and 0.4–0.8% year<sup>-1</sup> for beef (relative to 2010). The role of different drivers is region specific. Yet, supporting agricultural policies have played an important role in increasing yields in all countries, especially for crops. In cattle production, a key factor was the importance of commercial beef and milk production for the national or export market. Based on regional differences in drivers and yield developments, models that assess biomass potentials and impacts should take into account regional drivers, yield gaps, and potential policy pathways.

**Introduction**

The use of biomass for energy, chemicals, and materials is considered an important alternative to fossil resources (Chum et al. 2011; Harvey and Pilgrim 2011). For biomass to deliver a sizeable contribution, the availability of sufficient sustainable and affordable biomass feedstock is crucial. Assessment studies that have evaluated the current and future global availability of biomass resources show that the largest future potential contribution can come from energy crops grown on various types of land (Hoogwijk et al. 2005; Smeets et al. 2007). The most important land type is surplus agricultural land, which can be released through increased production efficiency

of food, animal feed or pasture. There is, however, disagreement about the availability of surplus agricultural land. Key uncertainties in predicting this area of land are technological progress in agricultural production systems and the related increases in crop and livestock yields (Dornburg et al. 2010; Slade et al. 2011; Batidzirai et al. 2012).

Several studies have investigated the effects of yields on the availability of surplus agricultural land and biomass potentials and impacts. For example, van Vuuren et al. (2009) assessed the impact of food crop yield changes on the global woody biomass potential in 2050. They found that an additional yield improvement of 12.5% compared to the baseline scenario resulted in an increase of the biomass potential from 150 to 230 EJ. Erb et al.

(2009) found that the biomass potential in 2050 would be 79 EJ year<sup>-1</sup> in the case of intermediate agricultural intensification and humane livestock rearing and 105 EJ year<sup>-1</sup> in the case of greater intensification of crop and livestock production.<sup>1</sup> Dornburg *et al.* (2010) estimated that improvements in agricultural management could account for 140 EJ year<sup>-1</sup> of the total biomass supply potential of 500 EJ year<sup>-1</sup> in 2050. Slade *et al.* (2011) derived from a review study that more than 1 Gha of high yielding agricultural land, equal to about 20% of the global agricultural land area in 2010, could be made available for bioenergy crops in 2050 if food crop yields increase at a higher rate than food demand and if the consumption of livestock products is limited.

The degree of yield improvements also affects the environmental performance of biomass production. Without sufficient improvements in yields, there is a large risk of direct or indirect land use change (DLUC and ILUC, respectively), which can result in high greenhouse gas (GHG) emissions (Searchinger *et al.* 2008; Laborde 2011). In addition, advances in agricultural production systems may also improve the performance of the agricultural sector as a whole. For example, Tilman *et al.* (2011) show that there is a significant potential in agriculture to reduce global land clearing, GHG emissions and nitrogen use through improved technology and adaption and transfer of high-yielding technologies to underyielding regions. Also, Havlík *et al.* (2014) show that the transition of livestock production toward more efficient systems would significantly decrease livestock-induced GHG emissions. These emission savings are mainly a result of a reduction in land use change (Havlík *et al.* 2014).

Models that assess land availability, land use change induced by biomass demand and other impacts of biomass production, such as those used in the studies mentioned above, generally base their crop yield projections on historical developments. Many of these studies also account for (a limited number of) endogenous drivers of future yields. These factors are related to, for example, climate change (Jaggard *et al.* 2010), crop or land prices (Eickhout *et al.* 2008; Rosegrant *et al.* 2008; EPA 2010; Khanna *et al.* 2011) or management changes like the increased use of fertilizer and other production factors (Eickhout *et al.* 2008; Beach *et al.* 2010; Mosnier *et al.* 2012). This diversity of factors reflects that in reality yield developments depend on numerous factors of various origins (e.g., economic, technological, and ecological). The question arises as to what role these different driving factors play, how they relate to each other and if their impact varies between regions. Moreover, productivity developments in the livestock sector have received much less attention in literature and modeling efforts than agricultural crops – despite the fact that livestock production accounts

for 70% of the total agricultural land and one third of the arable land area is used for feed crop production (Steinfeld *et al.* 2006). For this sector, the lack of insight into the possibilities to increase yields, the rate at which this can be established and the role of different driving factors is even larger.

Recently, de Wit *et al.* (2011) discussed what growth rates and maximum (sustainable) yields could be achieved in European agriculture. They assessed agricultural yield developments in the past five decades and compared these to policy developments, structural changes and trends in the use of production factors (inputs). De Wit *et al.* found that yield developments were clearly correlated to agricultural policy, but yield growth did not always coincide with more efficient use of inputs (de Wit *et al.* 2011). De Wit *et al.* focused on Europe and did not investigate other regions that are of critical importance in future biomass supply such as Latin America and sub-Saharan Africa (Hoogwijk *et al.* 2005; Smeets *et al.* 2007). Given the importance of yield projections in determining biomass supply and impacts, the aim of this study is to assess for seven countries in different world regions (i.e., Australia, Brazil, China, India, United States, Zambia, and Zimbabwe):

1. what the historical agricultural developments and their drivers are,
2. to what extent and at what growth rate crop and livestock product yields can improve in the future, and
3. how different settings and drivers can influence future yield developments.

These insights contribute to several aspects identified as a key to improving the assessment of biomass potentials and impacts, such as (1) the use of bottom-up analyses to enhance the understanding of current (agricultural) systems, options for improvement, the degree to which yields can be increased, drivers, and regional differences, and (2) a more explicit discussion of assumptions (including yields) (Batidzirai *et al.* 2012; Wicke *et al.* 2014).

## Methods

### Selection of agricultural products and producing countries

The potential area of surplus agricultural land is expected to be largely influenced by efficiency developments in the production of major agricultural products. Therefore, the agricultural developments are assessed for five crops that are most dominant in terms of global production and cultivated area: wheat, corn, rice, sugarcane, and soybean (FAOSTAT). In addition, for livestock, we only take into account beef and cow milk production since cattle uses most of the agricultural area for grazing. Pig and chicken

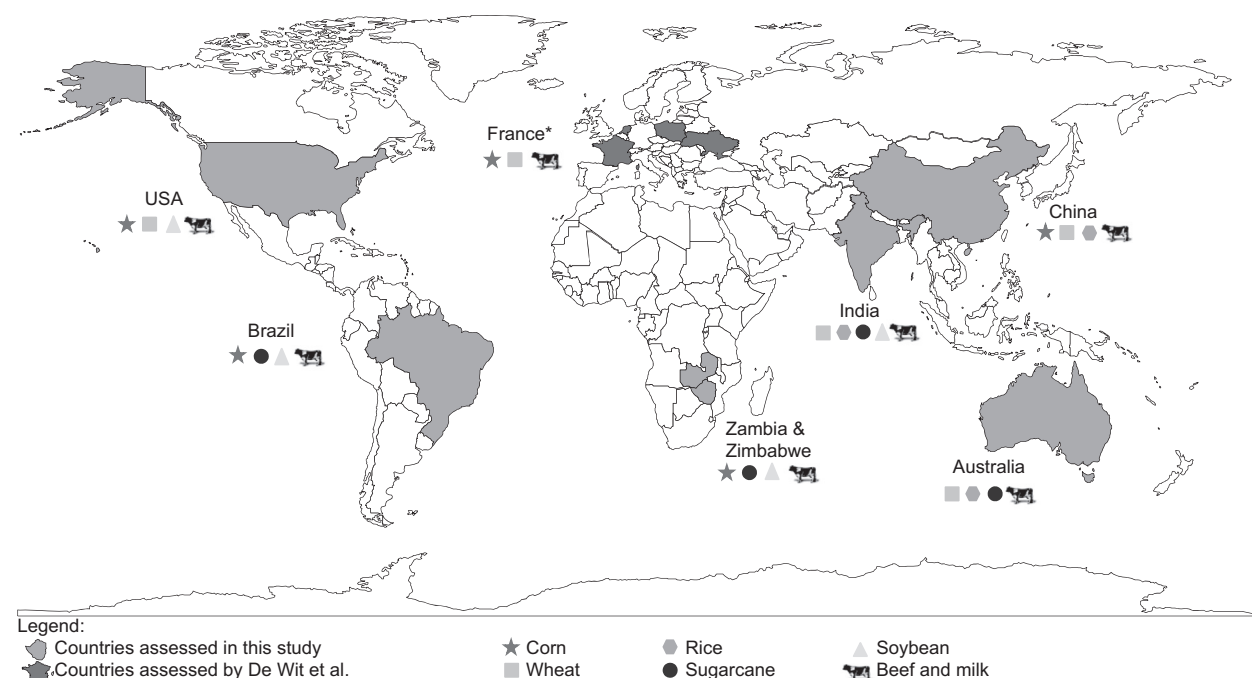
production are often landless, but land is required for producing feed crops (Seré and Steinfeld 1996). The area of cropland needed largely depends on the crop yields, which are already taken into account in this study. Therefore, pig and chicken production are not included in the assessment.

Agricultural developments are assessed in seven countries: Australia, Brazil, China, India, the United States, Zambia, and Zimbabwe (Fig. 1). There are two reasons for this selection. First, Brazil, China, India, and the United States are major producers of the selected crops and cattle products (FAOSTAT). Second, Australia, USA, Zambia, and Zimbabwe can potentially release a large area of agricultural land for biomass feedstock production (Hoogwijk et al. 2005; Smeets et al. 2007). de Wit et al. (2011) assessed agricultural developments in France, The Netherlands, Poland, and Ukraine. For comparison, we have included data about France in the results section. In addition, we compare the general findings from de Wit et al. with our own results.

### Historical developments in driving factors

The analysis starts with a description of the current status of agriculture in the selected countries and developments in driving factors that have taken place since 1961 (this part of the study is presented in Appendices 1–8). Based

on literature, the drivers of yield developments are classified into three types (Anderson 2010; Hengsdijk and Langeveld 2010; Neumann et al. 2010; Piesse and Thirtle 2010; Smith et al. 2010; de Wit et al. 2011): technological/management, economic, and institutional. Economic drivers are, for example, market developments and agricultural R&D investments. Institutional drivers include agricultural policies and governance systems. The discussion of economic and institutional drivers is based on literature review. For technological/management drivers, the following are assessed: labor intensity and level of mechanization, irrigation, nutrient, and pesticide use. These indicators are derived from time series data (1961–2010) collected from the UN Food and Agricultural Organization statistical division (FAOSTAT). These statistics are aggregated on a country level, for example, annual national consumption of fertilizers (tonne year<sup>-1</sup>). To enable comparison of the management levels between countries, the factors are expressed in average intensity per hectare of agricultural land, for example, the national number of tractors used divided by the total area of agricultural land. For cattle, another indicator for the management level or production intensity is the proportion of ruminants to the area of meadows and pastures (hereafter the ruminant density). This is also derived from FAO statistics. It is not chosen to evaluate the cattle density, because this neglects the importance of other ruminants in the occupation of meadows and pastures for grazing



**Figure 1.** Selected countries and agricultural products. \*France was earlier assessed by (de Wit et al. 2011), but for comparison, data for France are also presented in this study.

and hay. As a result of the feed requirements varying between ruminant species, the number of ruminants is expressed in livestock units (LU), where one unit represents the energy requirements for maintenance and production of a typical cow in North America. The livestock unit coefficients are obtained from the FAO (2011). The ruminant density is then calculated as the number of livestock units per hectare of meadows and pastures. The ruminants included are: buffaloes, camel, cattle, goats and sheep. The area of meadows and pastures consists of the total land area available for both for grazing and for the production of conserved forages. This approach thus also accounts for systems that combine grazing and confinement. In this study, we only consider a limited number of drivers that can be actively steered. Literature shows that more factors can influence yields, see the discussion.

### Historical yield and productivity developments

To assess historical yield trends and yield growth rates for the selected products and countries, time series data (1961–2010) are collected from FAOSTAT. The crop yield is defined as the annual production quantity per hectare of area harvested ( $\text{tonne ha}^{-1} \text{ year}^{-1}$ ); the beef yield is given in terms of carcass weight ( $\text{kg animal}^{-1}$ ); the milk yield is the annual milk production per cow ( $\text{kg animal}^{-1} \text{ year}^{-1}$ ). All numbers are national averages. The average beef and milk production per animal, however, are not the best indicators to study developments in livestock product yields. Beef and milk production can take place in different production systems ranging from pastoral to landless. But intensification does not always lead to higher beef or milk production per animal (e.g., because faster weight gain leads to shorter lifespans). Therefore, a better parameter for milk and beef yields would be the feed conversion efficiency (FCE,  $\text{kg animal product per kg feed intake}$ ). The use of the FCE, however, has also limitations. These are considered in the discussion.

Average annual yield growth rates are obtained by applying linear regression to the historical yield data and are presented per product, per country, per decade and for the entire period. Growth rates are both expressed in absolute growth per year (e.g.,  $\text{t ha}^{-1} \text{ year}^{-2}$ ) and in percentage per year (simple annual growth rate, relative to the initial year). Temporal shifts are identified for each product on country level and differences between products within a country are described. Explanations are sought by comparing the observed changes with the technological/management, economic, and institutional developments. In addition, developments in productivity of the total agricultural sector and of the total livestock sector are assessed and discussed. This productivity is defined as the

proportion of aggregated outputs to aggregated inputs (output–input ratio). To derive the aggregated inputs and outputs, the trend of all inputs and outputs in physical units is calculated as an index (base year 1961). From these indices, an (unweighted) average of all inputs and all outputs is calculated for each year. For the agricultural sector, the included inputs are: agricultural land, fertilizer and tractors; the outputs are: crops, meat, milk, and eggs. For the livestock sector, the inputs are: feed crops, meadow, and pasture land; the outputs are: meat, milk, and eggs.

### Future yield projections and the role of driving factors

Yield growth rates from projections in literature and models are compared to linear extrapolation of historical trends. It is discussed how yield projections are defined and how they can be improved based on the findings on historical driving factors. For each country, key factors are identified that may stimulate or limit future yield developments. To better understand what possible pathways could be defined for future yield developments, also the magnitude of yield gaps is taken into account. The yield gaps are derived from current yield levels and data on maximum attainable rain-fed or irrigated yields in 2020 as derived from the Global Agro-Ecological Zones database for the IPCC SRES B1 Scenario from the Australian Commonwealth Scientific and Research Organization (CSIRO) Mark 2 Mode (GAEZ Global Agriecological Zones).

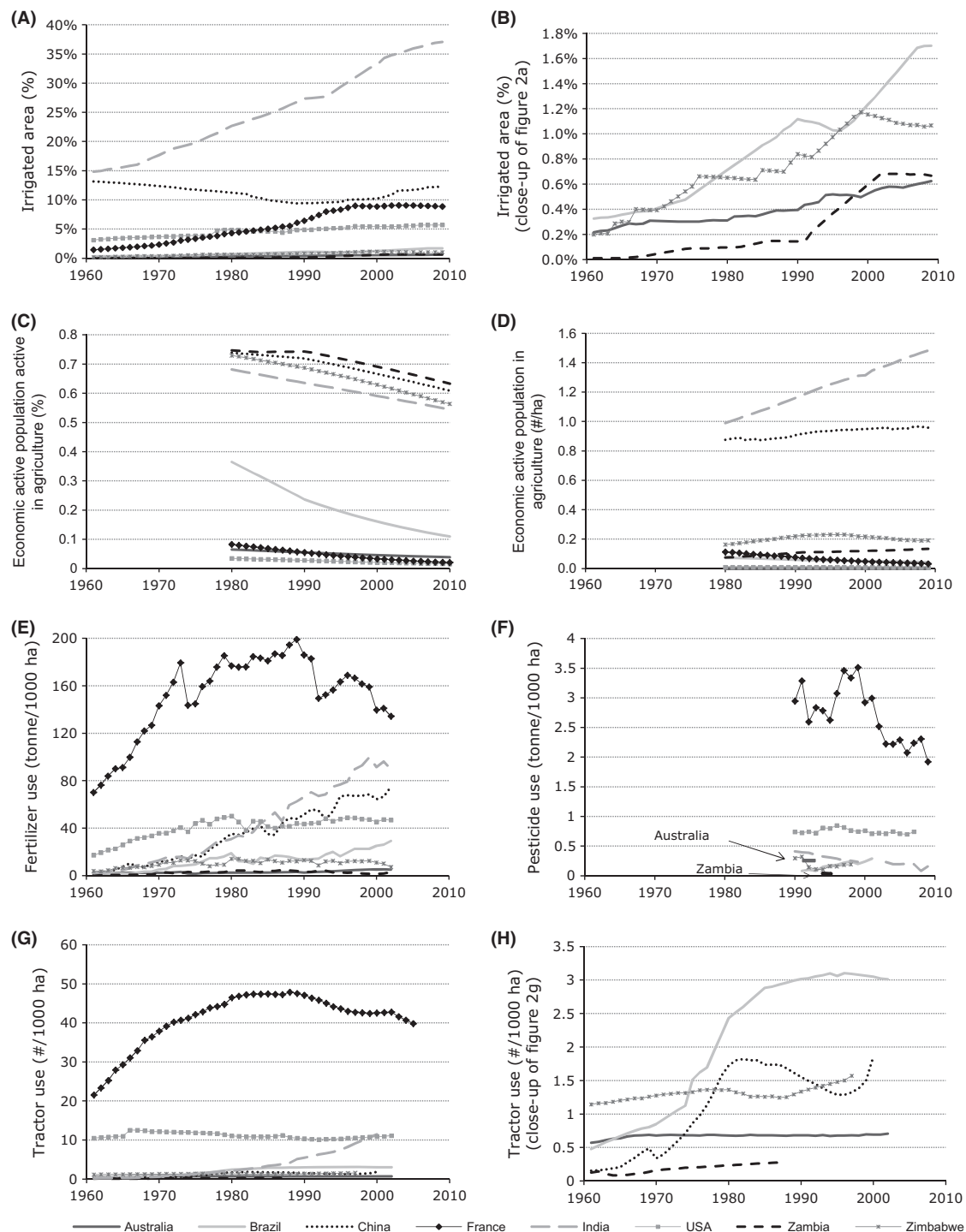
## Results

### Yield and productivity developments

For each country, historical developments in agricultural inputs and yields are assessed. For each country, the status of agriculture and the developments in the different driving factors are discussed in detail in Appendices 1–8. Here a synthesis of historical yield developments and driving factors is presented for the case of Zimbabwe. Syntheses for the other countries can be found in Appendices 2–7. The key findings for each country are presented and compared after the example of Zimbabwe.

### Example: developments and driving factors in Zimbabwe

Zimbabwe's first green revolution by commercial farmers (Eicher 1995; Langyintuo and Setimela 2009) is clearly represented by the increase of irrigated area and fertilizer use in the 1960s and early 1970s (Fig. 2). The yields of corn and soybeans only started to improve from the

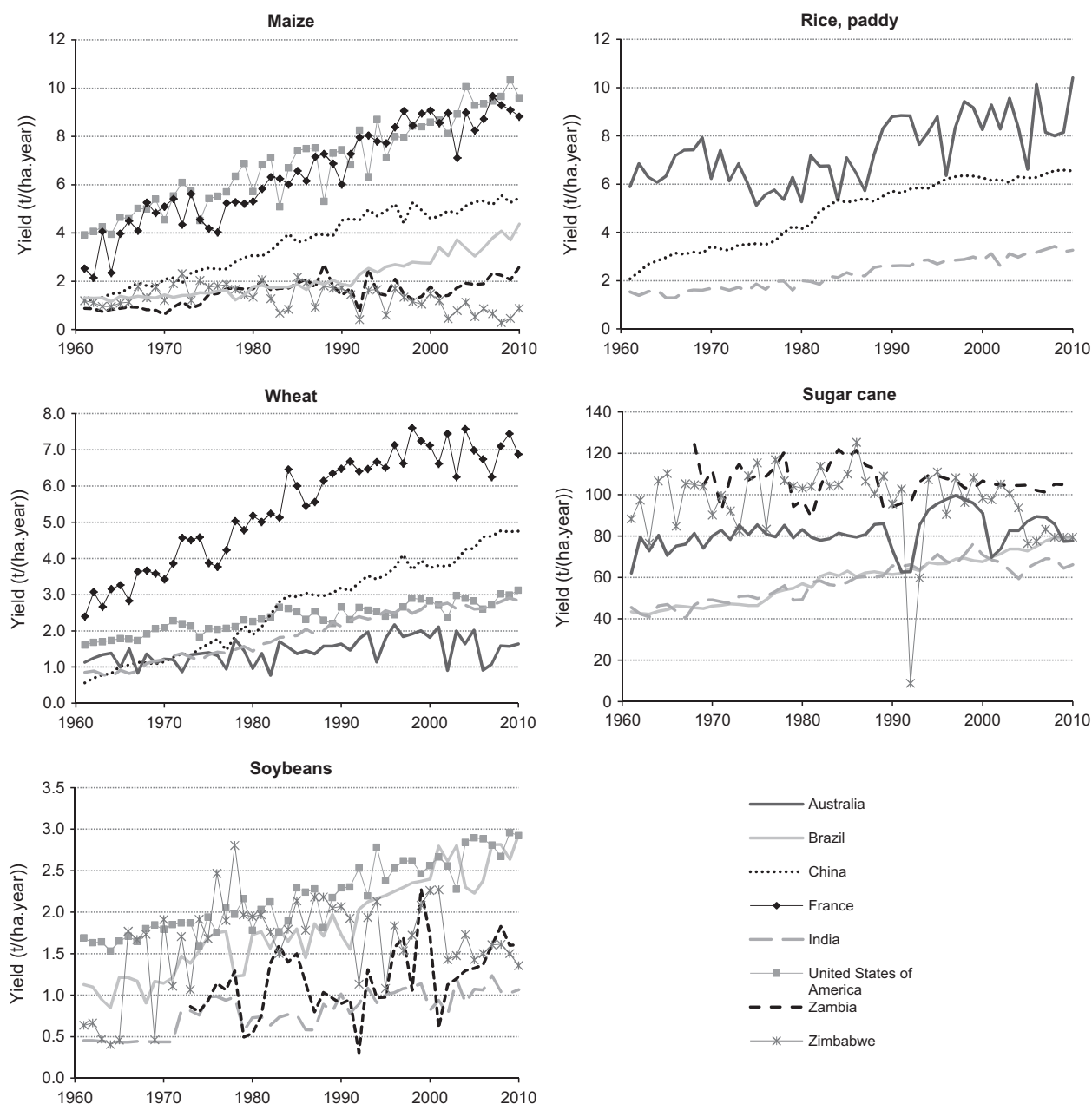


**Figure 2.** Development in agricultural inputs. All parameters are calculated from FAOSTAT data (FAOSTAT) according to the following definitions: (A) Agricultural area equipped for irrigation = Total area equipped for irrigation/Agricultural area. (B) Close-up of panel A, presenting a selection of the data to reveal differences between the countries at the lowest irrigation levels. (C) Labor share = Total economically active population in agriculture/Total economically active population. (D) Labor intensity = Total economically active population in agriculture/Agricultural area. (E) Fertilizer = Total fertilizers/Agricultural area. (F) Pesticides = (Insecticides Total + Herbicides Total + Fungicides and Bactericides Total)/Agricultural area. (G) Tractors = Agricultural tractors/Agricultural area. (H) Close-up of panel G, presenting a selection of the data to reveal differences between the countries at the lowest levels of tractor use. Note: when no data are shown for a certain country and/or year, no data is available for this country or year. Note: for tractors, the capacity or size of machinery is not taken into account.



second half of the 1960s (Fig. 3), which coincides with the shift from tobacco production to other crops because of export sanctions imposed in 1965 (Whitlow 1988; Eicher 1995) (also see Appendix 8). During the 1970s, corn yields declined again, while soy yields only fell down in 1979. In addition, irrigation levels stagnated and fertilizer use dropped in the 1970s. Thus, management conditions seem to be affected by the civil war (Whitlow 1985) and corn production suffered more from

this than soybean cultivation. Sugarcane yields appear to be even less affected by economic and political changes in the 1960s and 1970s. Apart from significant fluctuations, sugarcane yields have increased from 1960 until 1986. The improvement rate of  $0.9\%$  year<sup>-1</sup> in these years, however, is significantly lower compared to a growth rate of  $3.1\%$  year<sup>-1</sup> for corn and  $16.9\%$  year<sup>-1</sup> for soybeans between 1960 and 1980 (all relative to 1961), also see Table 1.



**Figure 3.** Historical yield developments (1961–2010) for the crops corn, paddy rice, wheat, sugarcane and soybeans (FAOSTAT).

**Table 1.** Absolute and relative growth in crop, beef and milk yields for the period 1961–2010 and per decade (based on FAO statistics).

Product	Country	Production Mt (kt)	Yield t ha <sup>-1</sup> year <sup>-1</sup> /kg animal <sup>-1</sup> year <sup>-1</sup>		Average annual yield change kg ha <sup>-1</sup> year <sup>-2</sup> /kg animal <sup>-1</sup> year <sup>-2</sup> /% year <sup>-1</sup>							
					Per decade <sup>3,4</sup>					Period		
			2010	1961	2010	1961–70	1971–80	1981–90	1991–00	2001–10	1961– 2010 <sup>3</sup>	1961– 2010 <sup>5</sup>
Corn	Brazil	56.1	1.3	4.4	12	21	23	85	101	55		
					0.9%	1.5%	1.3%	4.0%	3.2%	7.0%	1.6%	
	China	177.5	1.2	5.5	95	111	116	24	79	93		
					8.0%	5.4%	3.6%	0.5%	1.6%	7.3%	1.6%	
	France	14.0	2.5	8.8	325	33	83	179	101	131		
					13.4%	0.7%	1.4%	2.4%	1.2%	4.1%	1.4%	
	USA	316.2	3.9	9.6	132	84	63	159	156	117		
Rice, paddy					3.3%	1.6%	1.0%	2.2%	1.8%	2.9%	1.2%	
	Zambia	2.8	0.9	2.6	–11	102	4	–4	117	25		
					–1.2%	11.2%	0.2%	–0.3%	8.3%	2.8%	1.2%	
	Zimbabwe	1.2	1.2	0.9	54	–57	33	16	–39	–15		
					5.4%	–2.9%	2.4%	1.4%	–4.3%	–0.9%	–1.6%	
	Australia	0.2	5.9	10.4	127	–157	172	24	27	62		
					2.1%	–2.4%	2.8%	0.3%	0.3%	1.1%	0.7%	
Soybeans	China	197.2	2.1	6.5	127	105	108	83	56	93		
					5.5%	3.3%	2.3%	1.5%	0.9%	3.6%	1.3%	
	India	120.6	1.5	3.3	18	30	80	30	48	43		
					1.2%	1.8%	4.2%	1.1%	1.6%	3.4%	1.3%	
	Brazil	68.8	1.1	2.9	8	18	15	70	20	37		
					0.8%	1.3%	0.9%	3.8%	0.8%	4.1%	1.4%	
	India	12.7	0.5	1.1	–2	13	22	16	19	14		
Sugarcane					–0.4%	1.8%	3.4%	1.8%	2.0%	2.9%	1.2%	
	USA	90.6	1.7	2.9	22	19	25	22	42	27		
					1.4%	1.1%	1.3%	0.9%	1.7%	1.8%	1.0%	
	Zambia	0.0	0.9 <sup>1</sup>	1.6	0	–33	–40	134	100	17		
		(41.0)			0.0%	–4.0%	–3.0%	19.8%	11.0%	2.0%	1.2%	
	Zimbabwe	0.1	0.6	1.4	130	114	43	46	–45	12		
		(57.3)			30.0%	8.5%	2.5%	2.9%	–2.5%	0.9%	0.6%	
Wheat	Australia	31.5	62.2	77.7	947	–3	211	3475	811	221		
					1.3%	0.0%	0.3%	4.8%	1.0%	0.3%	0.3%	
	Brazil	716.2	43.4	79.2	399	1239	439	671	1081	775		
					0.9%	2.8%	0.7%	1.1%	1.5%	1.9%	1.0%	
	India	277.8	45.6	66.1	530	329	738	930	94	593		
					1.2%	0.7%	1.3%	1.4%	0.1%	1.4%	0.8%	
	Zambia	4.1	124.4 <sup>2</sup>	106.1	–6198	–27	–344	747	4	–152		
Wheat					–5.2%	0.0%	–0.3%	0.7%	0.0%	–0.1%	–0.1%	
	Zimbabwe	2.8	88.3	79.5	1071	1385	–649	4972	–2897	–270		
					1.2%	1.5%	–0.6%	7.5%	–2.9%	–0.3%	–0.3%	
	Australia	22.1	1.1	1.6	–7	16	42	42	–27	12		
					–0.6%	1.4%	3.3%	2.6%	–1.6%	1.0%	0.7%	
	China	115.2	0.6	4.7	65	82	90	79	126	88		
					10.0%	6.5%	3.7%	2.4%	3.0%	17.0%	1.8%	
Wheat	France	38.2	2.4	6.4	114	90	139	97	–9	98		
					4.3%	2.2%	2.7%	1.5%	–0.1%	3.2%	1.3%	
	India	80.7	0.9	2.8	43	26	58	45	19	47		
					5.8%	2.0%	3.5%	2.0%	0.7%	6.2%	1.5%	
	USA	60.1	1.6	3.1	49	6	–3	51	46	25		
					3.1%	0.3%	–0.1%	2.1%	1.8%	1.5%	0.8%	

**Table 1.** (Continued)

Product	Country	Production Mt (kt)	Yield t ha <sup>-1</sup> year <sup>-1</sup> /kg animal <sup>-1</sup> year <sup>-1</sup>		Average annual yield change kg ha <sup>-1</sup> year <sup>-2</sup> /kg animal <sup>-1</sup> year <sup>-2</sup> /% year <sup>-1</sup>						
			1961	2010	Per decade <sup>3,4</sup>					Period	
					1961–70	1971–80	1981–90	1991–00	2001–10	1961– 2010 <sup>3</sup>	1961– 2010 <sup>5</sup>
Beef	Australia	2.1	150	254	1.7	–0.9	4.0	1.5	2.5	2.1	
					1.1%	–0.5%	2.3%	0.7%	1.1%	1.4%	0.8%
	Brazil	7.0	192	238	0.1	–2.4	–0.1	3.2	4.1	0.8	
					0.0%	–1.2%	0.0%	1.6%	2.1%	0.4%	0.4%
	China	6.2	97	141	0.1	0.2	5.4	–2.4	1.3	1.2	
					0.1%	0.2%	5.8%	–1.6%	1.0%	1.3%	0.8%
	France	1.5	186	296	1.1	2.7	3.9	0.1	1.7	2.7	
					0.6%	1.3%	1.7%	0.0%	0.6%	1.5%	0.9%
	India	1.1	80	103	0.0	0.9	1.1	0.1	0.0	0.6	
					0.0%	1.1%	1.3%	0.1%	0.0%	0.8%	0.6%
Cow milk	USA	12.0	215	341	4.2	0.3	3.4	2.0	2.1	2.7	
					2.0%	0.1%	1.3%	0.7%	0.6%	1.3%	0.8%
	Zambia	0.1	190	160	–0.6	–2.7	0.0	0.0	0.0	–0.7	
		(60.8)			–0.3%	–2.0%	0.0%	0.0%	0.0%	–0.4%	–0.4%
	Zimbabwe	0.1	167	225	0.0	–2.4	6.2	3.8	0.0	1.6	
		(99.6)			0.0%	–1.4%	4.1%	2.1%	0.0%	1.1%	0.7%
	Australia	9.0	1985	5810	93	7	113	80	91	75	
					4.7%	0.3%	3.8%	1.9%	1.7%	4.0%	1.4%
	Brazil	30.7	707	1340	9	–7	8	51	19	12	
					1.2%	–0.9%	1.2%	6.9%	1.6%	2.0%	1.0%
Cow milk	France	23.3	2671	6278	73	47	114	93	30	84	
					2.8%	1.5%	3.0%	1.8%	0.5%	3.5%	1.3%
	China	36.0	1208	2882	6	55	–43	6	80	29	
					0.5%	4.6%	–2.3%	0.4%	3.5%	3.0%	1.2%
	India	50.0	424	1284	2	7	19	27	36	17	
					0.4%	1.4%	3.4%	3.7%	3.8%	6.0%	1.5%
	USA	87.5	3307	9595	125	95	136	147	147	128	
					3.8%	2.1%	2.5%	2.1%	1.8%	4.1%	1.4%
	Zambia	0.1	300	300	0	0	0	0	0	0	
		(88.5)			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Cow milk	Zimbabwe	0.4	406	430	–1	3	0	1	0	1	
					–0.3%	0.7%	–0.1%	0.1%	0.0%	0.2%	0.2%

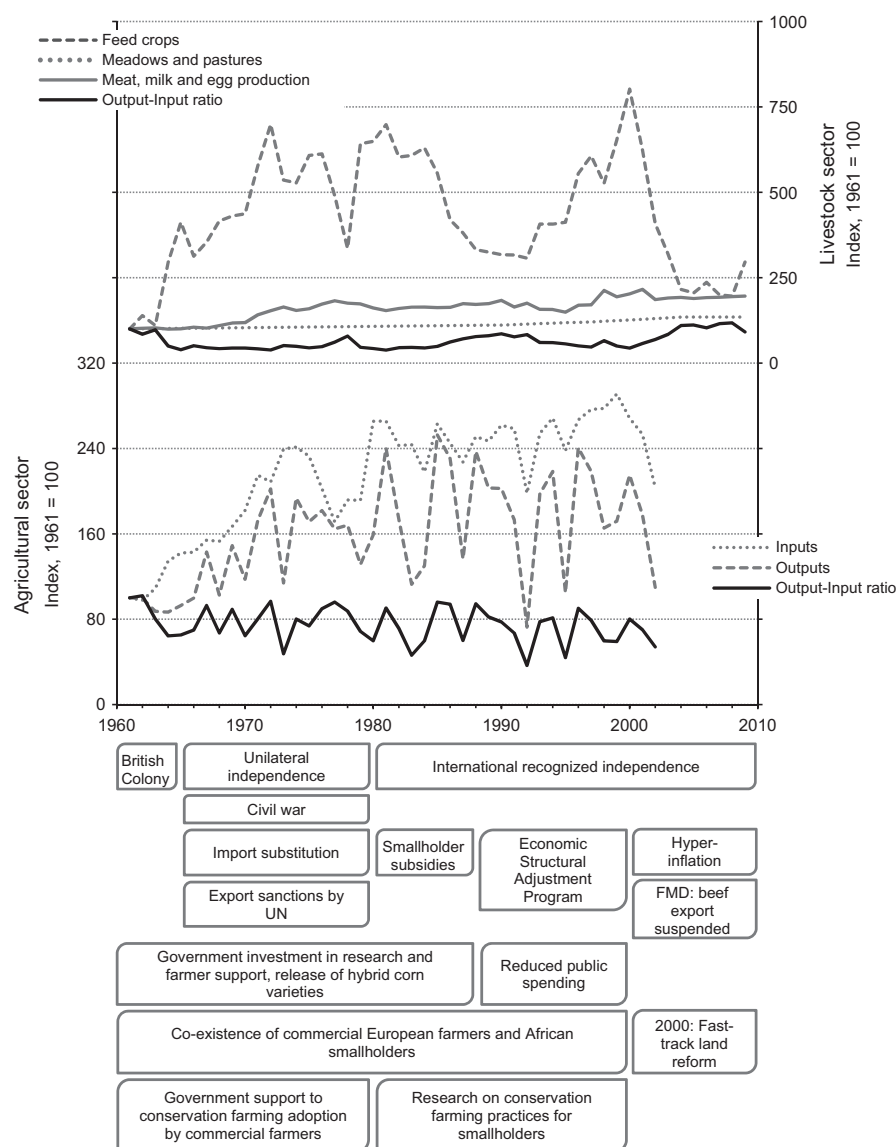
Negative growth in bold.

<sup>1</sup>Yield in 1973.<sup>2</sup>Yield in 1968.<sup>3</sup>The average annual yield change in terms of percentage is given relative to the first year of the selected period, that is, the average growth rate is expressed as a percentage of the estimated yield in the first year of selected period (e.g., from 1971–1980, the average annual growth of corn yield in Brazil was 1.5% of the yield level in 1971 as derived from linear regression).<sup>4</sup>Note that the yield growth rates per decade are calculated for a limited time period of 10 years. This means that the choice for a certain timeframe and outliers in the data can have significant influence on the result of the linear regression. The use of longer timeframes may show a very different trend in yield development.<sup>5</sup>Relative to 2010.

The introduction of smallholder support in the early 1980s led to a second green revolution (Eicher 1995), but this is not clearly reflected in the statistics. A major factor is the severe drought in 1983, resulting in a significant drop of corn and soybean yields. Good climate conditions in 1985 led to high yields (Eicher 1995). But due to the reduction of smallholder support, and maybe the decline of agricultural R&D as well (Eicher 1995), fertilizer use and crop yields

declined in the late 1980s and the 1990s. Remarkably, the area under irrigation increased in the same period. Due to a severe drought, crop yields plummeted in 1992 (Eicher 1995). With the fast-track land reform in 2000 (Matondi, 2012a), yields and input levels dropped further and continued declining in the following years. Overall, crop yields and also agricultural productivity (Fig. 4) have fluctuated considerably throughout the period 1961–2010.





**Figure 4.** Productivity developments in the Zimbabwean agricultural and livestock sector and institutional, economic and technological/management developments. Because of limited data, agricultural tractors are not included in the inputs and in the output-input ratio for the agricultural sector. (FMD, foot-and-mouth disease).

Considering cattle production, beef yields were stable in the 1960s and early 1970s, but declined during the civil war in the late 1970s (see Fig. A9 in Appendix 9). In the 1980s and 1990s, the yields improved at an average rate of 1.8% year<sup>-1</sup> (relative to 1981), but dropped temporarily during the drought of 1992. According to the FAO statistics, beef yields have stagnated since the hyper-inflation and outbreak of foot-and-mouth disease (Marquette 1997; Matondi, 2012b). Between 1960 and 1990, milk yields increased at a very low rate of 0.2% year<sup>-1</sup> (relative to 1961). Thus, it seems that technological improvements were limited while economic and political changes did not significantly affect milk yields either. After a small drop in 1992, yields peaked in 1993 and have stabilized since the late 1990s.

## Summary and comparison between countries

Over the past five decades, most crop yields showed an upward trend (Table 1). The yield growth rates, however, varied significantly between regions. Average yield growth rates over the period investigated (1961–2010) ranged in most cases between 0.7–1.6% year<sup>-1</sup> for crops, 1.0–1.5% year<sup>-1</sup> for milk and 0.4–0.8% year<sup>-1</sup> for beef (all relative to 2010). Highest rates were found for wheat in China (1.8% year<sup>-1</sup>), milk in India (1.5% year<sup>-1</sup>), and beef in France (0.9% year<sup>-1</sup>). The lowest rates for a crop are found for sugarcane (–0.3 to 1.0% year<sup>-1</sup>), for any one country the rates are lowest for Zimbabwe (–1.6 to 0.7% year<sup>-1</sup>). For comparison, in the European countries studied by de Wit et al. (2011), the average growth rates of wheat

are 1.0% year<sup>-1</sup> for Poland to 1.3% year<sup>-1</sup> for France (relative to 2010). This is lower compared to the wheat growth rates in China and India, but higher compared to the figures for wheat in Australia and the USA. Absolute wheat yield growth in France and the Netherlands (approximately 100 kg ha<sup>-1</sup> year<sup>-2</sup> (de Wit *et al.* 2011)), however, was higher compared to the four countries producing wheat in the present study. For beef, the absolute growth in France and Poland is comparable to the USA, but average growth rates in these European countries are higher than in all non-European countries assessed in this study (0.9% year<sup>-1</sup> for France and 1.2% year<sup>-1</sup> for Poland). Absolute and relative yield growth figures for beef in the Netherlands are comparable to Brazil.

In this study, the most observed trend over five decades for crop yield growth is linear. This is in accordance with other studies (Hafner 2003; Ray *et al.* 2013; Fischer *et al.* 2014). Yet, in each case, the analysis revealed periods during which yields improved at a higher rate compared to the long-term average as well as periods during which yield growth rates were lower than this average. In each case, technological as well as economic and institutional factors have played a role and these drivers often influenced each other. Yet, the importance and the effect of a driving factor varied from case to case. Table 2 gives an overview of the most important factors behind yield and productivity developments in each country (for more details, see Appendices 2–8; for France see de Wit *et al.* (2011)).

Improvements in agricultural technology and management have often led to considerable yield growth (Figs 2 and 3). Especially in China and India, large-scale adoption of new technologies (including high-yielding crops) resulted in high average yield growth rates (Appendices 4 and 5). In France and the United States, improved technologies resulted in considerable absolute yield improvements (Appendix 6). The technological improvements, however, included a significant increase in the use of inputs like fertilizer and often caused a decline in agricultural productivity (Fig. 5). In the cattle sector, yield improvements were often achieved through the increased use of feed crops. In Australia and Zimbabwe, however, the consumption of feed crops grew faster than the production of meat and milk, which led to a reduction in the productivity of the livestock sector. Other countries, like India and the USA were able to compensate for the higher input levels by increasing the production output levels of the livestock sector at a similar or even higher rate.

Economic factors often play a vital role in the improvement of agricultural technology. Investments in R&D enabled the development of new technologies. In most countries, these were mainly public investments. In the USA, also

private investments were very important (Appendix 6). These investments had already started in the period of industrial and agricultural protectionism. Only in Australia, industrial protectionism indirectly biased the agricultural sector and hindered improvements in production practices and crop yields (Appendix 2). The introduction of economic liberalization provided an incentive for many farmers to (further) improve yields and increase or stabilize agricultural productivity. In Australia, yields and yield improvement rates improved quickly after liberalization started. In Brazil and the USA, yield improvement rates reduced in the first instance but increased again after about ten years (Appendices 3 and 6). Agricultural production in China diversified after the reforms and yield improvements of predominant crops slowed down (Appendix 4). Commercial farmers in Zambia profited from liberalization as they were able to improve soybean yields at high rates, while corn yields of smallholders decreased (Appendix 7). For the cattle sector, the importance of commercial beef and milk production for the domestic or export market was found to be a key factor for yield improvements. In Australia and the USA, such markets already existed during the period of protectionism, while the beef market in Brazil has especially grown after economic liberalization (Appendices 2, 3 and 6). In France (and the EU as a whole), dairy markets got saturated and a quota on milk production was introduced. The number of dairy cows reduced significantly, but milk yields continued to increase through improved management (Huyghe 2012). This, however, led to a reduction in livestock productivity in terms of the output–input ratio.

In accordance with the findings of de Wit *et al.* (2011) for European countries, policies are found to be an important instrument in steering changes in the agricultural sector in the seven countries investigated in the present study. New technologies could be adopted by farmers because of farmer support programs, for example, in India (Appendix 5). Market liberalization policies created new markets for agricultural products, for example, in Australia (Appendix 2). In some cases, yield improvements have been attained by policies that were focused on a specific commodity: for example, in Zambia, the focus of policies on corn production during a long period resulted in significantly higher yield growth rates for corn compared to other crops (Appendix 7). In Brazil, the ProAlcool program positively affected sugarcane yields (Appendix 3). The import substitution policy for edible oils in India, especially stimulated the increase of soybean yields. In contrast to the successful implementation of policies in the above examples, Zimbabwe also shows the impact of a lack of good governance and stimulating policies. A civil war in the 1970s and economic reforms around the 1990s disrupted agricultural production and the economy. Due to

**Table 2.** Key driving factors behind historical yield and productivity development<sup>1</sup>.

	Driving factors	Effect on other driving factors	Effect on crops	Effect on cattle
Australia	<ul style="list-style-type: none"> <li>Market reforms, trade liberalization, opening of export markets</li> <li>Cattle: growth of export markets</li> </ul>	<ul style="list-style-type: none"> <li>+ Cattle management and technology</li> </ul>	<ul style="list-style-type: none"> <li>+ Rice and wheat yields</li> <li>+ Agricultural productivity</li> </ul>	<ul style="list-style-type: none"> <li>+/- Beef and milk yields</li> </ul>
Brazil	<ul style="list-style-type: none"> <li>Introduction of agri-environmental policies</li> <li>Industrial protection and fertilizer subsidies</li> <li>Economic reforms</li> </ul>	<ul style="list-style-type: none"> <li>+ Agricultural production, fertilizer use, irrigation</li> <li>+ Fertilizer use</li> <li>- &amp; +/- Fertilizer use</li> </ul>	<ul style="list-style-type: none"> <li>+/- Agricultural productivity</li> <li>+ Corn and soybean yields</li> <li>- Agricultural productivity</li> <li>- Corn and soybean yield growth rates</li> <li>+/- Agricultural productivity</li> <li>+ Yield growth rates corn and soybean</li> </ul>	<ul style="list-style-type: none"> <li>+ Milk and beef yields</li> <li>- Livestock productivity</li> <li>+ Decline in livestock productivity slowed down</li> <li>+/- Beef and milk yields</li> <li>+/- Beef and milk yields</li> </ul>
	<ul style="list-style-type: none"> <li>Opening of agricultural export markets</li> </ul>	<ul style="list-style-type: none"> <li>+ Fertilizer use</li> </ul>		<ul style="list-style-type: none"> <li>+ Beef and milk yield growth rate &amp; Livestock productivity increase</li> </ul>
China	<ul style="list-style-type: none"> <li>ProÁlcool program</li> <li>Agricultural reforms, public investments in infrastructure and R&amp;D</li> <li>Economic reforms</li> <li>Increased consumption of milk and dairy products</li> </ul>	<ul style="list-style-type: none"> <li>+ Tractor use, irrigation</li> <li>+ Irrigation, fertilizer use, mechanization</li> <li>+ Agricultural diversification</li> </ul>	<ul style="list-style-type: none"> <li>+ Sugarcane yields</li> <li>+ Yields</li> <li>- Yield growth rates</li> </ul>	<ul style="list-style-type: none"> <li>+ Beef and milk yields</li> <li>+ Milk yields</li> </ul>
France	<ul style="list-style-type: none"> <li>Protection of agricultural markets, stimulation of mechanization and fertilizer use</li> <li>Stimulation of modernization and scaling-up, land reforms</li> <li>Shift to high-yielding crops</li> </ul>	<ul style="list-style-type: none"> <li>+ Inputs</li> <li>+/- Fertilizer use</li> </ul>	<ul style="list-style-type: none"> <li>+ Yields</li> <li>- Agricultural productivity</li> </ul>	<ul style="list-style-type: none"> <li>+ Milk and beef yields</li> </ul>
	<ul style="list-style-type: none"> <li>Stimulation of modernization and scaling-up, land reforms</li> <li>Shift to high-yielding crops</li> </ul>	<ul style="list-style-type: none"> <li>+/- Fertilizer use</li> </ul>	<ul style="list-style-type: none"> <li>+ Yields &amp; Agricultural productivity</li> <li>+ Yields &amp; Agricultural productivity</li> </ul>	<ul style="list-style-type: none"> <li>+ Milk and beef yields</li> </ul>
	<ul style="list-style-type: none"> <li>Agri-environmental policy, reform of farmer support programs and stimulation of organic farming</li> </ul>	<ul style="list-style-type: none"> <li>- Inputs</li> </ul>	<ul style="list-style-type: none"> <li>- Yield growth rates</li> </ul>	<ul style="list-style-type: none"> <li>- Yield growth rates</li> </ul>
India	<ul style="list-style-type: none"> <li>Quotation milk production</li> <li>Public investments and subsidies</li> </ul>	<ul style="list-style-type: none"> <li>+ Inputs</li> </ul>	<ul style="list-style-type: none"> <li>+ Yields</li> <li>- Agricultural productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Livestock productivity</li> </ul>
USA	<ul style="list-style-type: none"> <li>Increased milk consumption</li> <li>Investment in R&amp;D, biotechnology</li> </ul>	<ul style="list-style-type: none"> <li>+ Livestock technology and management</li> </ul>	<ul style="list-style-type: none"> <li>+ Yields</li> </ul>	<ul style="list-style-type: none"> <li>+ Milk yields</li> <li>+ Beef and milk yields</li> </ul>
	<ul style="list-style-type: none"> <li>Trade liberalization and reform of farmer support policies</li> </ul>		<ul style="list-style-type: none"> <li>- Yield growth rates (during reforms)</li> <li>+ Yield growth rates (after reforms)</li> </ul>	
Zambia	<ul style="list-style-type: none"> <li>Growing milk market</li> <li>Agri-environmental programs</li> <li>Fertilizer subsidies</li> <li>Economic liberalization, elimination of fertilizer subsidies</li> <li>Conservation farming technologies</li> <li>Fertilizer Support Program</li> </ul>	<ul style="list-style-type: none"> <li>- Fertilizer use</li> <li>+ Fertilizer use</li> <li>- Fertilizer use</li> <li>+ Irrigation</li> <li>+ Fertilizer use</li> <li>+/- Irrigation</li> </ul>	<ul style="list-style-type: none"> <li>+ Agricultural productivity</li> <li>+ Corn yields</li> <li>- Corn yields</li> <li>+ Soybean yields</li> <li>+ Agricultural productivity</li> <li>- Agricultural productivity</li> <li>+ Corn yields</li> </ul>	<ul style="list-style-type: none"> <li>+ Milk yields</li> </ul>
Zimbabwe	<ul style="list-style-type: none"> <li>R&amp;D (commercial farmers)</li> <li>Civil war</li> <li>Economic reforms, reduction of smallholder support and of agricultural R&amp;D</li> <li>Economic crisis and fast track land reform</li> <li>FMD and ban on beef export</li> </ul>	<ul style="list-style-type: none"> <li>+ Irrigation &amp; Fertilizer use</li> <li>- Irrigation &amp; Fertilizer use</li> <li>- Fertilizer use</li> <li>- Inputs</li> </ul>	<ul style="list-style-type: none"> <li>- Yields</li> <li>- Yields</li> </ul>	<ul style="list-style-type: none"> <li>- Beef yields</li> </ul>
			<ul style="list-style-type: none"> <li>- Yields</li> </ul>	<ul style="list-style-type: none"> <li>- Beef yields</li> </ul>

FMD, foot-and-mouth disease.

<sup>1</sup>Effect: +, increase; - decrease; +/- stabilization.

the long-term unstable situation, crop yields and agricultural productivity have fluctuated heavily. In addition to agricultural policies aimed at economics and production, most countries have also introduced agri-environmental policies which aimed at, for example, enhanced quality of degraded agricultural lands (Australia, China, Zambia, Zimbabwe), balanced use of inputs (China, France) and controlled use and management of natural resources (Australia, India, the United States). In the USA, China, and Zambia, this led to improved agricultural productivity (Appendices 4, 6, and 7). In Australia, the productivity did not improve considerably compared to previous years (Appendix 2). In India, the productivity continued to decline due to weak enforcement of agri-environmental policies (Appendix 5).

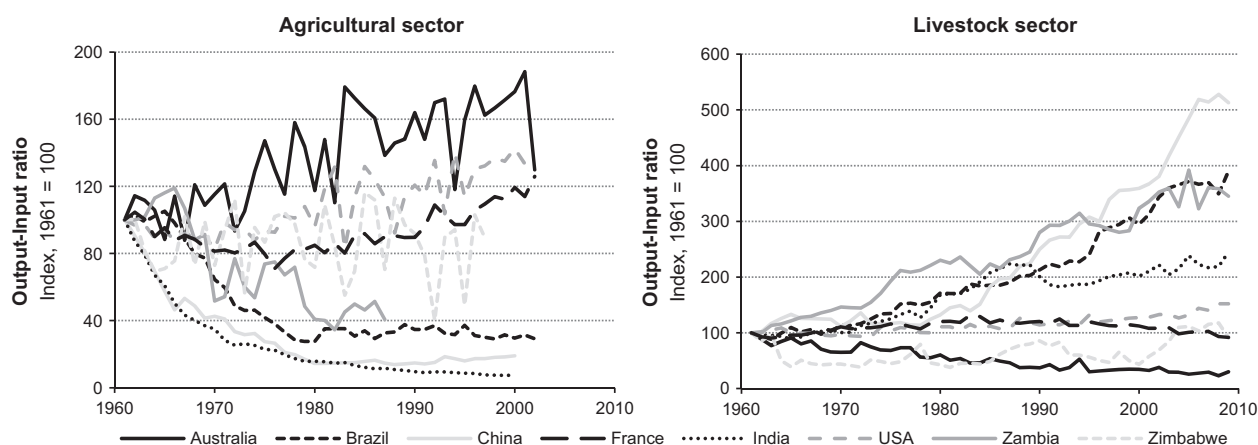
## Yield projections

### Crops

Models that assess biomass potentials and/or impacts of biomass production apply either only exogenous yield projections (determined by factors outside the model) or a combination of exogenously and endogenously (determined by the model based on internal factors) defined yield projections. The exogenous yield projections are based on historical trends. As mentioned in the previous section, the analysis of historical yield developments shows that the most observed trend for crop yield growth is linear. Yet, longer historical time series show that in, for example, the USA crop yield growth has not always followed the current linear trend (see

Fig. A11 in Appendix 9). Also, over shorter time frames, variability in the trend is found with periods of decline, stagnation and/or strong growth. Therefore, yield projections based on historical trends depend on the historical time frame taken into account. For example, Fischer *et al.* (2014) find global yield growth rates of 1.0% year<sup>-1</sup> for wheat, rice, and soybean and 1.5% year<sup>-1</sup> for corn based on the linear trend for 1991–2010. For the period 1961–2010, the present study finds global growth rates that are slightly higher for wheat, rice, and soybean (1.1–1.3% year<sup>-1</sup>) and lower for corn (1.3% year<sup>-1</sup>, all relative to 2010), see Table A1 in Appendix 9. Although these differences seem small, they may have considerable impact on future biomass potentials and impacts. This is illustrated by Fischer *et al.* (2014) who state that, in order to meet the projected food demand in 2050 with limited increase of real prices of crops, the minimum global yield growth rate for staple crops between 2010 and 2050 is 1.1% year<sup>-1</sup> relative to 2010 (Fischer *et al.* 2014). Higher growth rates of, for example, 1.3% year<sup>-1</sup> are preferred to account for factors that may influence supply and demand of crops, including increasing biofuel demand (Fischer *et al.* 2014). In model assessments, it is therefore important to make explicit what historical time frame is considered to define exogenous yield projections.

Although exogenous yield projections are based on historical trends, some models assume extrapolation of this trend (e.g., in (Jaggard *et al.* 2010)), while most models assume the overall future yield growth to slow down compared to the historical trend (e.g., in (Laborde 2011; OECD 2012)). Van Dijk and Meijerink (2014)



**Figure 5.** Comparison of developments in productivity (output-input ratio) of the agricultural and livestock sector in the seven selected countries. The input-output ratio is indexed to 100 for the year 1961. This means that when the ratio is higher than 100 in 1 year, the productivity has improved compared to 1961; when the ratio is lower than 100, the productivity has declined. For the agricultural sector the included inputs are: agricultural land, fertilizer and tractors; the outputs are: crops, meat, milk and eggs. For the livestock sector, the inputs are: feed crops, meadow and pasture land; the outputs are: meat, milk and eggs.

give several reasons for assuming decreasing yield growth. First, the opportunities for increasing yields and exploiting existing yield gaps are more and more exhausted (Searchinger et al. 2013). Also, investments in agricultural R&D have declined and considerable socio-economic constraints in many developing countries are considered to remain a limiting factor for yield growth (Alston et al. 2009; McIntyre et al. 2009; Alexandratos and Bruinsma 2012). Although these motivations are reasonable, these are mainly expectations about how different factors are likely to develop. There may, however, also be other possible pathways. Indeed, the present study shows that in the past 50 years, significant developments in technology, for example, mechanization, fertilizer use, and crop breeding, have driven yield improvements. But although these technologies are wide-spread now, there still exist considerable differences in technology level and yield gaps between regions (see first part of the results and Table A2 in Appendix 9). The present study and the study by de Wit et al. (2011) show that in regions where historical yield growth was high, the development and adoption of new technologies was primarily driven by policies (e.g., subsidies for farmers, trade liberalization and public investments in R&D). In regions where there is still room for considerable yield improvements, stimulating policies could thus play a vital role in materializing this potential. Similarly, other factors could also have a significant effect on future yield developments. The presence of different potential pathways shows that, in the assessment of future biomass potentials and the impacts of biomass production, it is important to investigate different scenarios and to include various endogenous driving factors.

To determine the endogenous yield projections, models relate yield change to driving factors like land or crop prices, climate change, or management. According to Dietrich et al. (2014), technological change is considered to be the key driver for yield change. There is, however, little consensus about the drivers of technological change and the influence of these drivers on yield change (Dietrich et al. 2014; Robinson et al. 2014). Therefore, the number of endogenous factors is generally limited in models, often to only one or two factors. As a result, the different technical, economic, and institutional driving factors are not covered well. Furthermore, the findings from the historical analysis make clear that future yield developments largely depend on how the different driving factors develop in each region. As the number of endogenous factors is generally limited, models do not properly distinguish different driving factors between regions. Important examples of how different drivers affect yield growth potentials are the following:

- In the case of corn in the USA, current yields have attained almost 80% of the *maximum attainable yield*<sup>2</sup> (see Table A2 on yield gaps, Appendix 9). Thus, it is likely that the current technological limits will constrain and slow down yield growth in the near future. Continuation of the historical yield improvement trend would require significant *technological progress*, for example, increase in the potential agroclimatic yield through biotechnology.
- On the other side of the spectrum, yields of rice and soy in India and corn and soy in Zambia and Zimbabwe are less than 40% of the maximum attainable yield. In various other cases, the yield gap is smaller but still leaves room for considerable yield improvements as well. In such situations, the historical analysis shows that accelerated yield growth compared to the longer term trend is possible under favorable circumstances with regard to, for example, governance.
- Zambia and Zimbabwe are examples of cases where *stable agricultural and trade policies* are needed to improve and support the agricultural sector and market and the economy in general. Under such conditions, farmers may be able to adopt improved technologies and management practices. As more advanced technologies and practices already exist, farmers could realize a significant acceleration in yield growth compared to the average trend over the past five decades.
- In Southern India, rice yields could be increased significantly if *management conditions* and *market access* would be improved (see Appendix 5 on agricultural characteristics). In Northern India, rice (and also wheat) is mainly produced on irrigated lands and yields are higher compared to Southern India. Ground water depletion, however, poses a risk to future yield improvements.
- An important measure to attain yield improvements in an environmentally sound way is *sustainable agricultural intensification*. In Australia, for example, management levels have been low relative to most other countries. The same is true for yield growth rates. Although intensification could have significant environmental impact, it is found that this can also be realized while improving the productivity, that is, increasing the crop production (output) per unit resource use (input), and reducing negative effects like emissions and water pollution (see also (Fischer et al. 2014; Hochman et al. 2013; de Wit et al. 2014)).

Thus, for future modeling work, detailed regional assessment of the most important driving factors for yield development and the implementation of more drivers are needed. For this purpose, Table 3 identifies some key drivers that may either limit or stimulate future yield improvements in each country assessed in this study.



**Table 3.** Key threats and opportunities for future yield improvements.

	Threats to future yield improvements	Opportunities for future yield improvements
Australia	Climate and climate change	Sustainable intensification of crop and livestock sector (see e.g., (Hochman et al. 2013))
Brazil	Weak enforcement or mitigation of land conservation policies	Intensification of cattle production
China	Decreasing water availability, loss of fertile land and land degradation	Expansion of region-specific policies, continuation or expansion of policies to improve productivity, increase of mechanization
India	Land degradation, decreasing water availability	Improvement of market access, management and production of smallholders in Southern India, enforcement of agri-environmental policies, improvement of productivity
USA	Lack of new advances in biotechnology: no significant improvements in the maximum attainable yields	Significant funding for and advances in biotechnology: shift of maximum attainable yields
Zambia	Soil erosion, climate variability	Stimulating policy; e.g., improvement of market access of smallholders (investment in infrastructure), increase in the adoption of conservation farming
Zimbabwe	Continuation of unstable economic situation, climate variability	Re-establishment of (beef) export markets: improvement of knowledge and production of smallholders

The factors are identified based on the historical assessment presented in the first part of the results section.

We highlighted the importance of stimulating policies, especially for Zambia and Zimbabwe earlier. The historical analysis showed that in all countries agricultural and trade policies play an important role in steering yield developments. Van Dijk and Meijerink (2014) show that in economic models, policies and institutions are included, but it seems that their effect on yields is not considered yet. Given our findings, it is important to include policies as a driving factor for yield changes in model assessments. For example, Dietrich et al. (2014) have attempted to implement endogenous yield change related to investments in R&D. Linking yield developments to R&D and other policy-related drivers could be used to define scenarios for different policy pathways and to evaluate their impact on yield changes. In addition, yield gap figures are a good indicator both for the degree of technological progress that can still be attained, and for the potential yield growth rates. It is useful to apply yield gaps in the models to define the yield development projections. For that, more research is needed on, for example, the (crop and region specific) correlation between yield gaps and yield growth rates. In the historical analysis, it was also found that yields have often fluctuated in the past and this affected the average yield growth rate. In current assessment models, projections are based on historical trends and the influence of fluctuations on the long-term trend is neglected. The regional identification of key drivers for yield developments could include an assessment of risk factors for yield fluctuations (e.g., the occurrence of extreme climate conditions), which can be taken into account in the yield projections.

A comparison of yield projections from global outlook studies in van Dijk and Meijerink (2014) shows that the projected yield growth varies significantly and depends

on the underlying assumptions made. The influence of underlying assumptions on yield projections is also illustrated by a comparison of yield projections from the integrated assessment model IMAGE (which is used for the assessment of biomass potentials and impacts; see van Vuuren et al. (2009)) and the economic model MIRAGE models (which is used for analyses on, land use change induced by biofuel targets; see Laborde (2011)). In Table A1 (Appendix 9), growth rates derived from the yield projections in IMAGE and MIRAGE are compared to the extrapolation of historical trends. Both models combine exogenous yield projections with endogenously determined yield changes. The exogenous yield projections used in IMAGE and MIRAGE assume that, on the global level, yield growth rates will slow down compared to the historical linear trend (Laborde 2011; OECD 2012). Nevertheless, the two models do not always agree on whether yields in a certain region or even globally will improve at a pace higher or lower compared to the linear growth trend. Large differences in projections between the models are found for corn and soybean in Brazil and rice in China. Also, the projected global growth rates from MIRAGE for corn, rice, and soybean are higher compared to the projections based on linear extrapolation of the historical trends from 1961–2010. In IMAGE, the global projections for wheat, corn, rice, and soybean result in lower yield growth rates compared to linear extrapolation. It is most likely that these contrasting results can be explained by differences in how endogenous yield changes are modeled. The insights from this and other studies would help to make the underlying assumptions for endogenous yield projections more explicit and detailed, and help to assess how yield projections are influenced by different assumptions.



In the introduction, several studies were mentioned that assess the influence of increased yields on the biomass potential. Van Vuuren et al. (2009), Erb et al. (2009) and Dornburg et al. (2010) used yield projections from the FAO (Bruinsma 2003), the presented yield projections from the IMAGE model are in line with these projections (OECD 2012)). Van Vuuren et al. (2009) and Dornburg et al. (2010) take this FAO scenario as baseline and assess the extra biomass potential from additional yield increases. Erb et al. (2009) however, assume that the FAO scenario represents a high intensification scenario and baseline yield improvements are lower. This shows that the perception of the baseline varies. This again underlines the importance to make assumptions more explicit. In addition, it is important to discuss each scenario and address under what conditions the projected yields and the resulting biomass potentials and impacts can be attained; the degree to which investments have to be increased, or required changes in policy. This is considered to be highly valuable for decision making.

## Beef and milk

As opposed to historical yield growth trends for crops often being linear, for beef and milk production, we only found linear trends for Australia, India, and the United States; these are countries where we found that yields had significantly improved over a longer time-frame because of the existence of a commercial market. The absence of a yield trend in the past makes it more difficult to define yield growth scenarios for the future. Also, compared to crops, less information can be found about the projections used in the models. Several studies, e.g. IMAGE (Bouwman et al. 2005; Eickhout et al. 2008), apply yield projections from the FAO, which are presented for aggregated world regions level in Wirsenius et al. (2010). A comparison of these projections with historical growth figures indicates that in developed regions, the average annual yield growth rate is projected to be significantly lower than in the last five decades. For example, in North America and Oceania, the increase in beef yield is projected to decline from 1.0% year<sup>-1</sup> in the period 1961–2005 to 0.2% year<sup>-1</sup> from 1997/99–2030. Also on the global level, yield growth of beef and milk will be slower compared to the historical trend. Acceleration of yield improvements is projected to especially take place in sub-Saharan Africa. In this region, the yield growth rates of milk are projected to increase from –0.4% year<sup>-1</sup> (1961–2005) to 0.8% year<sup>-1</sup> (1997/99–2030). In addition to the FAO projections, Wirsenius et al. (2010) defined an improved livestock production (ILP) scenario, assuming faster intensification of livestock production in low- and

medium income regions as a result of increased competition for land and stricter policies related to land use and livestock production. In this scenario, more regions (e.g., Asia) will realize accelerated yield increases compared to the past. Also on the global level, yield growth will increase from 0.9% year<sup>-1</sup> to 1.5% year<sup>-1</sup> for beef and from 0.5% year<sup>-1</sup> to 2.2% year<sup>-1</sup> for milk. The scenarios from FAO and Wirsenius et al. again illustrate regional differences, which should be taken into account in the models.

To define yield projections, it is again helpful to consider the potential role of different driving factors per region. In the historical assessment, it was found that the role of commercial livestock production for the domestic or export market is an important factor for explaining yield improvements. For modelling purposes, several scenarios could be defined for market development based on assumptions regarding the size and location of beef and milk consumption and production. In addition, the speed of yield improvements may be based on other driving factors like the possibilities for technological developments and the introduction of agri-environmental policies. Similar to crops, the technological improvement potential could be assessed through yield gap analysis. For livestock, however, no standardized methods exist to assess the yield gap (ILRI). One approach is similar to the conceptual framework for crops and is based on three groups of production factors; production defining (climate and animal genetic characteristics), production limiting (water and feed intake) and growth-reducing (diseases, pollutants) (van de Ven et al. 2003). This method is still new; the first calculations of potential beef production were recently conducted by van der Linden et al. (2013).

## Discussion

### FAO data

This study analyses a large amount of statistical data which is obtained from the FAOSTAT database. The quality of FAO data, however, can vary significantly. When available, the FAO presents *official data*, which means that the data are collected directly from the states. Yet, the data collection capacities and practices vary between countries and affect the reliability of the data. In addition, the concepts, definitions, coverage, and classifications used by the countries are not uniform and require harmonization to enable international comparison. When no official data is available, the FAO gives figures from secondary semiofficial or unofficial datasets or own estimations (FAOSTAT). With regard to crop yields used in this study, the amount of underlying data

that is nonofficial data is limited and mainly restricted to Zambia and Zimbabwe. In the case of milk and beef yields, secondary and estimated data are more common and also presented on a regular basis for Brazil, China and India (FAOSTAT). Sometimes these data seem to be artificial as yields remain constant over one to five decades (see for example yields from beef and milk production in Zambia and Zimbabwe, Fig. A9).

To get an impression of the reliability of FAO yield statistics, their consistency with USDA data was analyzed (Fig. A12, Appendix 9). In some cases, FAO and USDA diverge significantly. For example, in Zambia, corn yield development between 1961 and 1982 is highly uncertain; figures from the FAO show an increasing yield trend, while the USDA data presents a downward trend. This has significant impact on the interpretation of historical developments. The FAO data suggests that corn yield improvements started in the early 1970s with the introduction of fertilizer subsidies for smallholder farmers, while the USDA data implies that the yields were negatively affected by the new pricing and subsidy policies and only started to increase after the introduction of the first new corn varieties in the late 1970s. Differences between the two statistical sources were also found for soybean in Zimbabwe, milk in Brazil and China, and beef in China and India. Not all data sets could be compared as the USDA database had no statistics on milk and beef production in Zambia and Zimbabwe and on sugarcane yields. The varying quality and reliability must be taken into account when interpreting the results. Still, the FAO database is the most complete source for yield figures currently available.

### Yield indicators for cattle

With regard to cattle production, it is preferred to assess yield developments in terms of changes in feed conversion efficiency (FCE, kg animal product per kg feed intake) instead of beef or milk production per animal. The main problem of using the production level per animal is that this figure does not always reflect technological advancements. For example, an improved beef cattle production system may achieve faster weight gain and be able to reduce the cattle lifetime. As a result, the beef production per animal may remain constant or even reduce, while the total production can be increased. Also, de Wit *et al.* (2011) showed that beef yields in the Netherlands decreased in the 1990s and 2000s because of the large share of dairy cows that are optimized for milk and not for meat production. In the present study, the historical data show that the average yield per animal has continued to increase in the main cattle producing countries. The rates at which these yields have increased, however, are likely to differ from improvement rates in feed conversion efficiency.

Another reason why the use of the feed conversion efficiency is preferred is the underlying idea of this study that yield improvements have an important role in making land available for biomass production without increasing overall land use. While crop yields are directly related to land use, figures of beef or milk production per animal give no indication of the related land use. As feed consumption can be linked more directly to land use, the feed conversion efficiency would give a better insight in how developments in the cattle sector would influence land requirements.

Ideally, the FCE is measured over the lifetime of an animal because its value is not constant over time. To analyze historical developments in average FCE, a more simple but less accurate way is to calculate the feed conversion efficiency by dividing the produced amount of beef or milk by the gross feed intake. This feed intake is based on estimated energy requirements and the amount of energy supplied by feed inputs, factors that are highly depending on the production system. Therefore, the examination of developments in feed conversion efficiencies over time would require the allocation of animal populations and production quantities to the different production systems for at least several points in time, for example, building on previous work by Seré and Steinfeld (1996) and Bouwman *et al.* (2005). This was not feasible for the present study. As the carcass weight and annual milk production per animal are the best available data over a longer historical time period, these figures were used here to assess beef and milk yield developments. The same data were used by de Wit *et al.* (2011) and Wirsenijs *et al.* (2010) to study livestock yield growth rates.

### Yield projections and assessment of biomass potentials

This study investigated historical developments in yields and their drivers and provides suggestions for how potential studies can better account for yield developments and driving factors. The assessment focused on three types of driving factors: technological/management, economic, and institutional. Other factors, however, may also influence yield developments. Climate change, for example, may either have a positive or negative effect on yield growth depending on the location (see e.g., Jaggard *et al.* (2010)). Also, several studies indicate that yield improvement rates of crops are related to the GDP level of a country (Hafner 2003; Powell and Rutten 2013). This correlation, however, does not necessarily mean that GDP itself is a driver of yield development. It is more likely that GDP is an indicator of other driving factors, such as market conditions and technology levels, which are included in the present study.

As shown in the section about yield projections, historical yield growth rates depend on the time frame considered. This is also seen when comparing the yield growth rates for France as calculated in this study and in de Wit *et al.* (2011). For wheat, for example, the present study found a growth rate of 4.3% year<sup>-1</sup> (114 t ha<sup>-1</sup> year<sup>-1</sup>) for the period 1961 to 1970 while de Wit *et al.* found a growth rate of 5.2% year<sup>-1</sup> (136 t ha<sup>-1</sup> year<sup>-1</sup>) for the period 1961 to 1969. Thus, the yield growth rates are highly sensitive to the timeframe applied, especially in the case of short time frames. The growth rates should thus be considered with great care and only be used as an indicator of the extent of yield growth or decline. Nevertheless, both studies show that the yield growth rates are very useful to assess the impact of driving factors on yield developments.

Although the historical assessment gives important insights into how different factors may influence future yield developments, it is not possible to predict future yield growth rates. The insights can thus only be used to assess how yields may develop under certain conditions. Particularly the application of endogenous factors and scenarios is useful to assess how yield developments change under different assumptions and how this affects biomass potentials. As mentioned in the section about yield projections, it is important to translate each scenario to conditions for meeting the projected yield developments. This can help identify (regional) strategies for increasing yields.

Finally, in addition to yields, there are also other factors that may affect biomass production potentials. For example, market developments and incentives could influence the balance between crop and livestock production on the one hand and biomass production on the other hand. Also, sustainability criteria could affect the area of land that is excluded from biomass production. An overview of more key factors is provided by Dornburg *et al.* (2010). Similar to the drivers for yield developments, it is important to make the assumptions regarding these factors explicit. Also, the application of scenarios could be useful.

## Conclusions

Global, sustainable biomass production potentials of energy crops largely depend on the future availability of surplus agricultural lands made available through yield improvements in crop and livestock production. This study analyzed the pace and direction of historical yield developments between 1961 and 2010 in Australia, Brazil, China, India, the United States, Zambia, and Zimbabwe. Furthermore, it assessed the technological, economic, and institutional driving forces behind these developments and explored

how the insights gained can help to improve the modeling of future yields.

This study showed that historical yield growth (especially of crops) has often followed a linear trend. Mainly, the average yield improvement rates for crops and milk were between 0.7% and 1.6% year<sup>-1</sup>. For beef, the rates were lower (maximum of 0.8% year<sup>-1</sup> in Australia; all relative to 2010). In all cases, yields and yield growth rates have fluctuated to various degrees. Large fluctuations were especially found for crops when driving factors changed strongly (e.g., extreme climate conditions in Australia). Also, in each case, the analysis revealed periods during which yields improved at a higher rate compared to the long-term average as well as periods during which yield growth rates were lower than this average. The periods of high yield growth, for example, 8.5% year<sup>-1</sup> for soybean in Zimbabwe in the 1970s, show that relatively fast improvements can be attained in cases where the yield gap is still large. Such significant improvements can especially be realized under favorable conditions with regard to economics and governance that stimulate improvements in agricultural technology and management. The future development of yields depends on how driving factors will change in each region.

The historical assessment shows that all three types of driving forces have influenced yield changes. The importance and the effect of each factor, however, is country- and even regional- specific. Overall, supporting agricultural policies have played an important role in increasing yields. Examples of successful policies are subsidies to stimulate adoption of new technologies, trade liberalization (resulting in increased demand for agricultural products which stimulated investments and innovations in the agricultural sector) and public investments in R&D. In some periods and countries, such policies were absent or eliminated (e.g., Australia in the 1960s and Zambia in the 1990s). As a result, yields stagnated or declined. Although agricultural policies led to yield increases in many cases, they failed to improve output-input ratios (i.e., unsuccessful to realize more efficient use of resources like fertilizers). Some countries like the USA and (to a lesser extent) China were able to increase this productivity by implementing specific agri-environmental policies. Other countries adopted such policies as well, but the result largely depended on the success to enforce these policies (e.g., productivity stabilized in Australia, but no effect was seen in India). The importance of policies in steering yields was especially high for crops. With regard to yield improvements in cattle production, a key factor was the importance of commercial beef and milk production for the national or export market. But policy and market can be closely related: in many cases, trade liberalization created new markets, which stimulated investments and resulted in improved yields as demonstrated in, for example, Brazil.

Current models that assess biomass potentials and impacts only take into account one or a limited number of endogenous factors influencing yields. Also, an explicit discussion of the assumptions behind yield projections is lacking, which hampers a comparison of yield projections between the models. Several suggestions are made to improve the models and thereby our understanding of potential future pathways for agricultural yield developments and for sustainable biomass production. First, scenarios based on regional assessment of key factors for yield development, as conducted in this study, could help to gain more insight in potential pathways and regionally differentiated effects. Second, to define such scenarios, yield gap figures are an important indicator of possible technological progress and the potential rate of yield improvement. Also, different policy strategies should be included and tested in the scenarios. Finally, the assessment of important factors for yield development could help to make the underlying assumptions of yield projections more explicit. The implementation of these suggestions will help to identify policy options and preconditions for specific development pathways.

## Acknowledgments

The authors thank Vassilis Daioglou (Utrecht University and PBL Netherlands Environmental Assessment Agency) for sharing yield data from the IMAGE model. David Laborde is thanked for sharing data from the MIRAGE model. This research was conducted within the research program “Knowledge Infrastructure for Sustainable Biomass”, which is funded by the Dutch Ministries of ‘Economic Affairs’ and ‘Infrastructure and the Environment’.

## Conflict of Interest

None declared.

## Notes

<sup>1</sup> Assuming continuation of current trends in diet and crop land area expansion.

<sup>2</sup> Maximum attainable yield: the yield resulting from combining (1) the constraint-free potential agroclimatic yield with regard to temperature, radiation, and soil moisture conditions prevailing in the specific region and (2) reduction factors related to climate (e.g., pests and diseases), soil and terrain conditions, and assumptions regarding the management level (GAEZ Global Agri-Ecological Zones). Generally, it is assumed that there is a minimum yield gap where the actual yield level is equal to the economically attainable yield. Fischer *et al.* (2014) consider this economically attainable yield to be about 23%

below the maximum attainable yield. Larger yield gaps are assumed to be ‘economically exploitable yield gaps’. These caps could (largely) be closed with existing technologies (Fischer *et al.* 2014).

<sup>3</sup> The high growth rate for soybean yields is also related to the drought induced yield drop in 1992. Without this outlier in the dataset, however, the improvement rate is still 12.2 % year<sup>-1</sup>. Sugarcane yields were not considerably affected by the drought.

## References

- Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. Food and Agricultural Organisation of the United Nations, Rome, Italy. ESA working paper no. 12-03.
- Alston, J. M., J. M. Beddow, and P. G. Pardey. 2009. Agricultural research, productivity, and food prices in the long run. *Science* 325:1209–1210.
- Alston, J. M., J. S. James, M. A. Andersen, and P. G. Pardey. 2010a. A Brief History of U.S. Agriculture. Pp. 9–21. *in* J. M. Alston, J. S. James, M. A. Andersen and P. G. Pardey, eds. *Persistence Pays*. Springer, New York, NY.
- Alston, J. M., J. S. James, M. A. Andersen, and P. G. Pardey. 2010b. Research funding and performance. Pp. 137–185 *in* J. M. Alston, J. S. James, M. A. Andersen and P. G. Pardey, eds. *Persistence Pays*. Springer, New York, NY.
- Alston, J. M., J. S. James, M. A. Andersen, and P. G. Pardey. 2010c. The federal role. Pp. 187–236 *in* J. M. Alston, J. S. James, M. A. Andersen and P. G. Pardey, eds. *Persistence Pays*. Springer, New York, NY.
- Anderson, K. 2010. Globalization’s effects on world agricultural trade, 1960–2050. *Philos. Trans. Royal Soc. B: Biol. Sci.* 365:3007–3021.
- Anderson, K., and W. Martin. 2009. 9 China and Southeast Asia. Pp. 359–387 *in* K. Anderson, ed. *Distortions to agricultural incentives: A global perspective, 1955–2007*. The International Bank for Reconstruction and Development/The World Bank, Washington, DC.
- Anderson, K., and A. Valdés. 2009. 7 Latin America and the Caribbean. Pp. 289–322 *in* K. Anderson, ed. *Distortions to Agricultural Incentives: A Global Perspective, 1955–2007*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC.
- Anderson, K., R. Lattimore, P. J. Lloyd, and D. MacLaren. 2009. 5 Australia and New Zealand. Pp. 289–322 *in* K. Anderson, ed. *Distortions to Agricultural Incentives: A Global Perspective, 1955–2007*. The International Bank for Reconstruction and Development/The World Bank, Washington, DC.
- ASTI Data Tool version 1.1 [Internet]. ASTI Agricultural Science and Technology Indicators [accessed 2013 23 August]. Available at: <http://www.asti.cgiar.org/data/>.



- Baer, W. 1972. Import Substitution and Industrialization in Latin America: experiences and Interpretations. *Latin Am. Res. Rev.* 7:95–122.
- Banerjee, O., A. J. Macpherson, and J. Alavalapati. 2009. Toward a policy of sustainable forest management in Brazil: a historical analysis. *J. Environ. Develop.* 18:130–153.
- Bao, J. 2011. Dairy production in diverse regions | China. Pp. 83–87. *in* J. W. Fuquay, ed. *Encyclopedia of Dairy Sciences* (Second Edition), Academic Press, San Diego.
- Barros, S. 2013. Brazil Biofuels Annual: Annual Report 2013. USDA Foreign Agricultural Service, Sao Paulo; BR13005. Available at: [http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual\\_Sao%20Paulo%20ATO\\_Brazil\\_9-12-2013.pdf](http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_9-12-2013.pdf).
- Batidzirai, B., E. M. W. Smeets, and A. P. C. Faaij. 2012. Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. *Renew. Sustain. Energy Rev.* 16:6598–6630.
- Beach, R. H., D. Adams, R. Alig, J. Baker, G. S. Latta, and B. A. McCarl, et al. 2010. Model Documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG). RTI International. Available at: [http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG\\_Model\\_Documentation\\_Aug2010.pdf](http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf)
- Blandford, D., and R. N. Boisvert. 2006. 16 Policy for agricultural adjustment in the United States. Pp. 237–253 *in* D. Blandford and B. Hill, eds. *Policy reform and adjustment in the agricultural sectors of developed countries*. CAB International, Wallingford, Oxfordshire, UK.
- Bonaglia, F. 2009. Zambia: Sustaining agricultural diversification. *OECD J. Gen. Pap.* 2009:103–131.
- Bouwman, A. F., K. W. van der Hoek, B. Eickhout, and I. Soenario. 2005. Exploring changes in world ruminant production systems. *Agric. Syst.* 84:121–153.
- Bowman, M. S., B. S. Soares-Filho, F. D. Merry, D. C. Nepstad, H. Rodrigues, and O. T. Almeida. 2012. Persistence of cattle ranching in the Brazilian Amazon: a spatial analysis of the rationale for beef production. *Land Use Policy* 29:558–568.
- Bruinsma, J. 2003. World agriculture: towards 2015/2030. An FAO perspective. Earthscan Publications Ltd., London, UK.
- Carmo Oliveira, J. D.. 1986. Trade policy, market ‘distortions’, and agriculture in the process of economic development Brazil, 1950–1974. *J. Dev. Econ.* 24:91–109.
- Carpentier, C. L., and D. E. Ervin. 2002. USA. Pp. 95–139 *in* F. Brouwer and D. E. Ervin, eds. *Public concerns, environmental standards and agricultural trade*. CAB International, Wallingford, Oxfordshire, UK.
- Carvalho, J. 1991. Agriculture, industrialization and the macroeconomic environment in Brazil. *Food Policy* 16:48–57.
- Cederberg, C., D. Meyer, and A. Flysjö. 2009. Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production. Swedish Institute for Food and Biotechnology (SIK), Göteborg, Sweden. 792.
- Chambers, W. B.. 2002. World trade and concerns for the human environment. Pp. 39–55. *in* F. Brouwer and D. E. Ervin, eds. *Public concerns, environmental standards and agricultural trade*. CAB International, Wallingford, Oxfordshire, UK.
- Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, et al. 2011. Bioenergy. Pp. 209–332 *in* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and von Stechow C., eds. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, UK and New York, NY.
- Dietrich, J. P., C. Schmitz, H. Lotze-Campen, A. Popp, and C. Müller. 2014. Forecasting technological change in agriculture—an endogenous implementation in a global land use model. *Technol. Forecast. Soc. Chang.* 81:236–249.
- Van Dijk, M., and G. W. Meijerink. 2014. A review of global food security scenario and assessment studies: results, gaps and research priorities. *Global Food Sec.* 3:227–238.
- Dixon, J., A. Gulliver, and D. Gibbob. 2001. *Farming Systems and Poverty: Improving farmers’ livelihoods in a changing world*. FAO and World Bank, Rome and Washington, DC.
- Djurfeldt, G., E. Aryeetey, and A. C. Isinika. 2011. *African Smallholders: Food Crops, Markets and Policy*. CAB International, Wallingford, Oxfordshire, UK.
- Dornburg, V., D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, M. Banse, et al. 2010. Bioenergy revisited: key factors in global potentials of bioenergy. *Energy Environ. Sci.* 3:258–267.
- Doyle, P. T., and C. R. Stockdale. 2011. DAIRY FARM MANAGEMENT SYSTEMS | Seasonal, Pasture-Based, Dairy Cow Breeds. Pp. 29–37. *in* J. W. Fuquay, ed. *Encyclopedia of Dairy Sciences* (Second Edition), Academic Press, San Diego.
- Eicher, C. K. 1995. Zimbabwe’s maize-based Green Revolution: preconditions for replication. *World Dev.* 23:805–818.
- Eickhout, B., J. C. M. van Meijl, A. A. Tabeau, and E. Stehfest. 2008. The Impact of Environmental and Climate Constraints on global food supply. Netherlands Environmental Assessment Agency (MNP)/Agricultural Economics Research Institute (LEI), Bilthoven/The Hague, The Netherlands.
- EPA. 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. Environmental Protection Agency, Washington, DC. EPA-420-R-10-006.

- Erb, K., H. Haberl, F. Krausmann, C. Lauk, C. Plutzer, and J. K. Steinberger, et al. 2009. Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely—a scoping study. Commissioned by Compassion in World Farming and Friends of the Earth UK. Institute of Social Ecology, Vienna, Austria. Social Ecology Working Paper No. 116.
- FAO. 2011. Guidelines for the preparation of livestock sector reviews. Animal Production and Health Guidelines. FAO, Rome. Report No. 5.
- FAOSTAT [Internet]. FAO [updated 2014; accessed 2012–2014]. Available at: <http://faostat.fao.org>.
- Ferreira, J., R. Pardini, J. P. Metzger, C. R. Fonseca, P. S. Pompeu, G. Sparovek, et al. 2012. Towards environmentally sustainable agriculture in Brazil: challenges and opportunities for applied ecological research. *J. Appl. Ecol.* 49:535–541.
- Fischer, R. A., D. Byerlee, and G. O. Edmeades. 2014. Crop yields and global food security: will yield increase continue to feed the world? Australian Centre for International Agricultural Research, Canberra, Australia.
- GAEZ Global Agri-Ecological Zones [Internet]. Food and Agriculture Organisation of the United Nations (FAO) and International Institute for Applied Systems Analysis (IIASA) [updated 2014; accessed 2014 19 February]. Available at: <http://gaez.fao.org/Main.html#>.
- Gulati, A., and G. Pursell. 2009. 10 India and other South Asian Countries. Pp. 389–415 in K. Anderson, ed. *Distortions to Agricultural Incentives: A Global Perspective, 1955–2007*. The International Bank for Reconstruction and Development / The World Bank, Washington, DC.
- Hafner, S. 2003. Trends in maize, rice, and wheat yields for 188 nations over the past 40 years: a prevalence of linear growth. *Agric. Ecosyst. Environ.* 97:275–283.
- Hagbladh, S., and G. Tembo. 2003. Conservation farming in Zambia. International Food Policy Research Institute, Washington, DC, USA. EPTD Discussion Paper No. 108. Available at: <http://www.ifpri.org/sites/default/files/publications/eptdp108.pdf>
- Harvey, M., and S. Pilgrim. 2011. The new competition for land: food, energy, and climate change. *Food Policy* 36:S40–S51.
- Havlik, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, et al. 2014. Climate change mitigation through livestock system transitions. *Proc. Natl Acad. Sci. USA* 111:3709–3714.
- Hawkes, C., and S. Murphy. 2010. 2. An overview of global food trade. Pp. 16–32. in C. Hawkes, C. Blouin, S. Henson, N. Dräger and L. Dubé, eds. *Trade, Food, Diet and Health: Perspectives and Policy Options*. Wiley Blackwell, Oxford.
- Hawkes, C., S. Friel, T. Lobstein, and T. Lang. 2012. Linking agricultural policies with obesity and noncommunicable diseases: A new perspective for a globalising world. *Food Policy* 37:343–353.
- Hengsdijk, H., and J. W. A. Langeveld. 2010. Yield trends and yield gap analysis of major crops in the world. Statutory Research Tasks Unit for Nature & the Environment (WOT Natuur & Milieu), Wageningen, The Netherlands. WOT-werkdocument 170.
- Hochman, Z., P. S. Carberry, M. J. Robertson, D. S. Gaydon, L. W. Bell, and P. C. McIntosh. 2013. Prospects for ecological intensification of Australian agriculture. *Eur. J. Agron.* 44:109–123.
- Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg. 2005. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass Bioenergy* 29:225–257.
- Howard, J. A., and C. Mungoma. 1996. Zambia's stop-and-go revolution: the impact of policies and organizations on the development and spread of maize technologies. International Development Working Paper No. 61. MSU Agricultural Economics, Michigan.
- Huyghe, C. 2012. Country Pasture/Forage Resources Profiles. France [Internet]. FAO [updated 2012; accessed 2015 5 February]. <http://www.fao.org/ag/agp/AGPC/doc/Counprof/France/france.htm#4.RUMINANT>.
- ILRI 2014. Closing livestock yield gaps in the developing world: imperatives for people and the planet [Internet]. ILRI [updated 2014; accessed 2014 26 June]. Available at: <http://www.slideshare.net/ILRI/smith-gfsc-apr2014>.
- Jaggard, K. W., A. Qi, and E. S. Ober. 2010. Possible changes to arable crop yields by 2050. *Philos. Trans. Royal Soc. B: Biol. Sci.* 365:2835–2851.
- Jayne, T. S., J. Govereh, M. Wanzala, and M. Demeke. 2003. Fertilizer market development: a comparative analysis of Ethiopia, Kenya, and Zambia. *Food Policy* 28:293–316.
- Karplus, V. J., and X. W. Deng. 2008a. Transformation in China's Agriculture in the Twentieth Century. Pp. 27–44 in V. J. Karplus and X. W. Deng, eds. *Agricultural biotechnology in China: origins and prospects*. Springer, New York.
- Karplus, V. J., and X. W. Deng. 2008b. Agricultural biotechnology takes root in China. Pp. 55–77 in V. J. Karplus and X. W. Deng, eds. *Agricultural biotechnology in China: origins and prospects*. Springer, New York.
- Khanna, M., C. L. Crago, and M. Black. 2011. Can biofuels be a solution to climate change? The implications of land use change-related emissions for policy. *Interface Focus* 1:233–247.
- Laborde, D. 2011. Assessing the land use change consequences of European biofuels policies. International Food Policy Research Institute, Washington, DC. Available at: [http://trade.ec.europa.eu/doclib/docs/2011/october/tradoc\\_148289.pdf](http://trade.ec.europa.eu/doclib/docs/2011/october/tradoc_148289.pdf).



- Lamers, P., C. N. Hamelinck, M. Junginger, and A. P. C. Faaij. 2011. International bioenergy trade—A review of past developments in the liquid biofuel market. *Renew. Sustain. Energy Rev.* 15:2655–2676.
- Langyintuo, A. S., and P. Setimela. 2009. Assessing the effectiveness of a technical assistance program: the case of maize seed relief to vulnerable households in Zimbabwe. *Food Policy* 34:377–387.
- van der Linden, A., G. W. J. van de Ven S. J. Oosting, van Ittersum M. K., and de Boer I. J. M.. 2013. Can we extend yield gap analysis to livestock production? First International Conference on Global Food Security (poster presentation); 29 Sept–2 Oct 2013; Noordwijkerhout, The Netherlands.
- Marongwe, L. S., I. Nyagumbo, K. Kwazira, A. Kassam, and T. Friedrich. 2012. Conservation agriculture and sustainable crop intensification: A Zimbabwe Case Study. *Int. Crop Manag.* 17:1–29.
- Marquette, C. M. 1997. Current poverty, structural adjustment, and drought in Zimbabwe. *World Dev.* 25:1141–1149.
- Martinelli, L. A., R. Naylor, P. M. Vitousek, and P. Moutinho. 2010. Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future. *Curr. Opin. Environ. Sustain.* 2:431–438.
- Matondi, P. B. 2012a. 1. Understanding Fast Track Land Reforms in Zimbabwe. Pp. 1–17 in P. B. Matondi, ed. *Zimbabwe's fast-track land reform*, 1st edn. Zed Books, London.
- Matondi, P. B. 2012b. 5. Complexities in understanding agricultural production outcomes. Pp. 130–160 in P. B. Matondi, ed. *Zimbabwe's fast-track land reform*, 1st edn. Zed Books, London.
- Matondi, P. B. 2012c. *Zimbabwe's fast-track land reform*. Zed Books, London, UK; New York.
- McCormick, M. E.. 2011. Dairy farm management systems I non-seasonal, pasture optimized, dairy cow breeds in the United States. Pp. 38–43 in J. W. Fuquay, ed. *Encyclopedia of dairy sciences* (Second Edition). Academic Press, San Diego.
- McIntyre, B. D., H. R. Herren, J. Wakhungu, and R. T. Watson. 2009. *Agriculture at Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development - Global Report*. IAASTD, Washington, DC.
- Mosnier, A., P. Havlík, H. Valin, J. S. Baker, B. C. Murray, S. Feng, et al. 2012. The Net Global Effects of Alternative U.S. Biofuel Mandates: Fossil Fuel Displacement, Indirect Land Use Change, and the Role of Agricultural Productivity Growth — Nicholas Institute. Nicholas Institute for Environmental Policy Solutions, Durham, NC. NI R 12-01. Available at: <http://nicholasinstitute.duke.edu/climate/policydesign/net-global-effects-of-alternative-u.s.-biofuel-mandates>.
- Mukherjee, S., and D. Chakraborty. 2012. Editors' introduction: the Indian growth story: towards a sustainable development? Pp. 1–18 in S. Mukherjee and D. Chakraborty, eds. *Environmental scenario in India: successes and predicaments: Routledge Studies in Ecological Economics*. UK; Routledge, Abingdon, Oxon.
- Neumann, K., P. H. Verburg, E. Stehfest, and C. Müller. 2010. The yield gap of global grain production: a spatial analysis. *Agric. Syst.* 103:316–326.
- OECD. 2012. *OECD Environmental Outlook to 2050*. OECD publishing. Available at: <http://dx.doi.org/10.1787/9789264122246-en>.
- Pelletier, N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agric. Syst.* 103:380–389.
- Piesse, J., and C. Thirtle. 2010. Agricultural R&D, technology and productivity. *Philos. Trans. Royal Soc. B: Biol. Sci.* 365:3035–3047.
- Pink, B. 2012. 2012 Year book Australia. Australian Bureau of Statistics (ABS), Canberra.
- Pletcher, J. 2000. The politics of liberalizing Zambia's Maize Markets. *World Dev.* 28:129–142.
- Powell, J. P., and M. Rutten. 2013. Convergence of European wheat yields. *Renew. Sustain. Energy Rev.* 28:53–70.
- PSD Online [Internet]. USDA Foreign Agricultural Service [accessed 2013 September]. Available at: <http://www.fas.usda.gov/psdonline/psdQuery.aspx>.
- Quick Stats [Internet]. USDA National Agricultural Statistics Service [accessed 2013 September]. Available at: [http://quickstats.nass.usda.gov/?source\\_desc=CENSUS](http://quickstats.nass.usda.gov/?source_desc=CENSUS).
- Ray, D. K., N. D. Mueller, P. C. West, and J. A. Foley. 2013. Yield trends are insufficient to double global crop production by 2050. *PLoS ONE* 8(6):e66428.
- Robinson, S., van Meijl H., D. Willenbockel, H. Valin, S. Fujimori, T. Masui, et al. 2014. Comparing supply-side specifications in models of global agriculture and the food system. *Agricult. Econ.* 45:21–35.
- Rosegrant, M. W., C. Ringler, S. Msangi, T. B. Sulser, T. Zhu, and S. A. Cline. 2008. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description*. International Food Policy Research Institute, Washington, D.C. Available at: <http://www.ifpri.org/sites/default/files/publications/impactwater.pdf>.
- Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, et al. 2008. Use of U.S. Croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238–1240.
- Searchinger, T., C. Hanson, J. Ranganathan, B. Lipinski, R. Waite, and R. Winterbottom, et al. 2013. *Creating a Sustainable Food Future. A menu of solutions to sustainably feed more than 9 billion people by 2050*, World Resources Report 2013–14: Interim Findings. World Resources Institute (WRI), Washington, DC.

- Seré, C., and H. Steinfeld. 1996. World Livestock Production Systems: Current status, issues and trends. Food and Agriculture Organization of the United Nations, Rome. FAO Animal Production And Health Paper 127. Available at: <http://www.fao.org/docrep/004/W0027E/W0027E00.HTM>.
- Shah, A. 2012. Agriculture and environment in India Policy implications in the context of North-South trade. Pp. 219–242 in S. Mukherjee and D. Chakraborty, eds. Environmental scenario in India: successes and predicaments. Routledge, Abingdon, Oxon, UK.
- Silvis, H., and C. van Rijswijk. 2002. Agricultural policies and trade liberalisation. Pp. 11–37. in F. Brouwer and D. E. Ervin, eds. Public concerns, environmental standards and agricultural trade. CAB International, Wallingford, Oxfordshire, UK.
- Slade, R., R. Saunders, R. Gross, and A. Bauen. 2011. Energy from biomass: the size of the global resource. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London, UK.
- Smeets, E. M. W., A. P. C. Faaij, I. M. Lewandowski, and W. C. Turkenburg. 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* 33:56–106.
- Smith, P., P. J. Gregory, D. van Vuuren, M. Obersteiner, P. Havlík, M. Rounsevell, et al. 2010. Competition for land. *Philos. Trans. Royal Soc. B: Biol. Sci.* 365:2941–2957.
- Stattman, S. L., O. Hospes, and A. P. J. Mol. 2013. Governing biofuels in Brazil: a comparison of ethanol and biodiesel policies. *Energy Pol.* 61:22–30.
- Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's long shadow: environmental issues and options. FAO, Rome, Italy.
- Stringer, R., and K. Anderson. 2002. Australia. Pp. 181–214 in F. Brouwer and D. E. Ervin, eds. Public concerns, environmental standards and agricultural trade. CAB International, Wallingford, Oxfordshire, UK.
- Tauger, M. B. 2011. *Agriculture in World History*, 1st edn. Routledge, New York, NY.
- Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* 108:20260–20264.
- Trewing, D.. 2004. Chapter 14 – Agriculture. Pp. 417–456. in D. Trewing, ed. 2004 Year book Australia, Volume 86. Australian Bureau of Statistics (ABS), Canberra.
- Veeck, G., C. W. Pannell, C. J. Smith, and Y. Huang. 2011. *China's Geography: Globalization and the Dynamics of Political, Economic, and Social Change*, 2nd ed.. Rowman & Littlefield Publishers, Plymouth, UK.
- van de Ven, G. W. J., N. de Ridder, H. van Keulen, and M. K. van Ittersum. 2003. Concepts in production ecology for analysis and design of animal and plant–animal production systems. *Agric. Syst.* 76:507–525.
- van Vuuren, D. P., J. van Vliet, and E. Stehfest. 2009. Future bio-energy potential under various natural constraints. *Energy Pol.* 37:4220–4230.
- Whitlow, R. 1985. Conflicts in land use in Zimbabwe: political, economic and environmental perspectives. *Land Use Policy* 2:309–322.
- Whitlow, R. 1988. Soil erosion and conservation policy in Zimbabwe: past, present and future. *Land Use Policy* 5:419–433.
- Wicke, B., F. van der Hilst, V. Daioglou, M. Banse, T. Beringer, S. Gerssen-Gondelach, et al. 2014. Model collaboration for the improved assessment of biomass supply, demand, and impacts. *GCB Bioenergy*.
- Wint, G. R. W., and T. P. Robinson. 2007. *Gridded livestock of the world 2007*. FAO, Rome, Italy. Available at: <http://www.fao.org/docrep/010/a1259e/a1259e00.htm>.
- Wirsenius, S., C. Azar, and G. Berndes. 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agric. Syst.* 103:621–638.
- de Wit, M., M. Londo, and A. Faaij. 2011. Productivity developments in European agriculture: relations to and opportunities for biomass production. *Renew. Sustain. Energy Rev.* 15:2397–2412.
- de Wit, M. P., J. P. Lesschen, M. H. M. Londo, and A. P. C. Faaij. 2014. Greenhouse gas mitigation effects of integrating biomass production into European agriculture. *Biofuels, Bioprod. Biorefin.* 8:374–390.

## Appendix 1

### Historical Developments in Global Agricultural Sector

In the first half of the 20th century, global agriculture had been affected by weather crises (droughts, floods, famines, plant, and animal diseases), the great depression in 1930, and two world wars (Tauger 2011; Hawkes *et al.* 2012). Later, after a decolonization process during the 1950s–1960s, the agricultural sector in former colonies was also underperforming (Hawkes *et al.* 2012). At the same time, agriculture had to fulfill an important role in supporting the industrialization process by providing cheap food to urban work force (Hawkes and Murphy 2010; Hawkes *et al.* 2012). As a result, during the 1940s–1970s, governments aimed to increase their production and continue the modernization and mechanization of agricultural systems which had started in the 19th century (Tauger 2011). To support and protect agricultural production and prices, states adopted agricultural protection policies. Since the 1950s, many developed countries imposed strong state controls on agriculture and trade through instruments like import tariffs, export subsidies and producer support (Hawkes and Murphy 2010; Smith *et al.* 2010; de Wit *et al.* 2011). These policy instruments guaranteed a minimum return to farmers and compensated for price differences between the internal and global market (Hawkes and Murphy 2010; de Wit *et al.* 2011). Developing and industrializing countries heavily taxed agricultural exports and protected producers from import competition (Hawkes *et al.* 2012). Rapid economic growth facilitated investments in agricultural R&D, which led to breeding of high-yielding crop varieties, increasing application of fertilizers and irrigation, and mechanical innovations (Piesse and Thirtle 2010; Tauger 2011; de Wit *et al.* 2011). This is referred to as the Green Revolution. By the 1970s, the Green revolution and state intervention resulted in overproduction in developed countries. Some less developed countries like China and Brazil were also able to increase agricultural production at a higher rate than population growth. But other developing countries (especially in Africa) lagged behind and suffered from underproduction (Hawkes *et al.* 2012).

In the last 25 years, both developed and developing countries have begun to reform their agricultural policies, which has resulted in growing international trade of agricultural products.

Trade liberalization started with the first General Agreement on Tariffs and Trade (GATT) in 1947. Although the trade of agricultural products was subject

of international negotiations, it was typically excluded from multilateral trade agreements until 1990 (Hawkes and Murphy 2010; Hawkes *et al.* 2012). In 1995, the Uruguay Round Agreement on Agriculture (AoA) came into effect and imposed measures on signatory countries to open their agricultural markets (Hawkes and Murphy 2010; Hawkes *et al.* 2012). Another issue that remained unresolved in negotiations was the question how policies for sustainable development and environmental protection could be aligned with and integrated in trade regulations. Although environmental stewardship is a global issue, the interests in multilateral negotiations are diverse. While developed countries emphasize the need for an environmental reform of trade regulations, developing countries are mainly concerned with questions related to market access, dumping, and agricultural subsidies (Chambers 2002). As will be shown in the next sections, this diversity in interests is also reflected in the varying degree of adoption and enforcement of agri-environmental policies in the selected countries.

## Appendix 2

### Australia

#### Agricultural characteristics

Australia is a dry continent. Its climatic zones range from a tropical Northern region, through an arid interior, to a temperate Southern region (Pink 2012). The wet northern summer conditions allow beef cattle grazing and sugarcane production (east coast). The drier southern summer conditions favor wheat production, and grazing of sheep and dairy and beef cattle (Pink 2012). Rice is mainly grown in the Southeast of Australia (Pink 2012). About 10% of the agricultural area is cultivated (cropping and sown pastures and grasses) (Pink 2012; FAOSTAT). The remaining area consists of permanent pastures and meadows for livestock grazing (FAOSTAT). The majority of the farms are engaged in either livestock farming or grain growing (Pink 2012).

The management levels are low by OECD standards. Until the early 1980s, about 3.5% of the cultivated land (arable land) was equipped for irrigation. From the late 1980s, this share increased to about 5.5% in recent years (FAOSTAT). Irrigation is mainly applied for vegetables and fruits, rice, and also sugarcane (Stringer and Anderson 2002; Pink 2012). Because low rainfall limits the returns on fertilizer expenditure, fertilizer use is relatively low (Stringer and Anderson 2002), see Figure 2. The highest rates of fertilizer and pesticide are applied in horticulture (fruits and vegetables) (Stringer and Anderson 2002).

The average ruminant density on pastures is very low (see Fig. A10 in Appendix 9). Beef cattle are mainly held in Northern Australia, where production is extensive and the technology level low. In the South, production is more intensive. This is illustrated by higher stocking rates per hectare, improved pastures, and the use of fodder crops and animal health products (Pink 2012).

Dairy production mainly takes place in the south eastern high-rainfall coastal areas and is based on year round pasture grazing. Feedlot-based dairying is expanding, but is still uncommon (Pink 2012). Between 1980 and 2000, farmers switched to another dairy cattle breed (Doyle and Stockdale 2011).

### Economic and institutional developments

Compared to other OECD countries, Australia has been more protective to industry for most of the 20th century. The country did not participate in the General Agreement on Tariffs and Trade (GATT) between 1947–1979. In the 1950s and 1960s, Australia's policies were focused on industrial protectionism, characterized by price support, and trade protection (e.g., import restrictions on manufacturing products). These policies isolated farmers from national and international market signals (Stringer and Anderson 2002) and resulted in indirect disincentives for agriculture (Anderson *et al.* 2009). The subsidies and protection provided to the agricultural sector were limited and could not offset these disincentives (Anderson *et al.* 2009).

From the 1970s, Australia has been reforming its trade policies (Anderson *et al.* 2009). The past two decades have been a period of especially rapid total factor productivity (TFP) growth (Anderson *et al.* 2009). One important factor explaining the increase is the openness of the Australian economy to trade and investment (Fischer *et al.* 2014).

In 2002, Stringer and Anderson (2002) mentions that “four-fifths of the Australian agricultural production is exported”. The main export markets are the United States and Asia (Stringer and Anderson 2002).

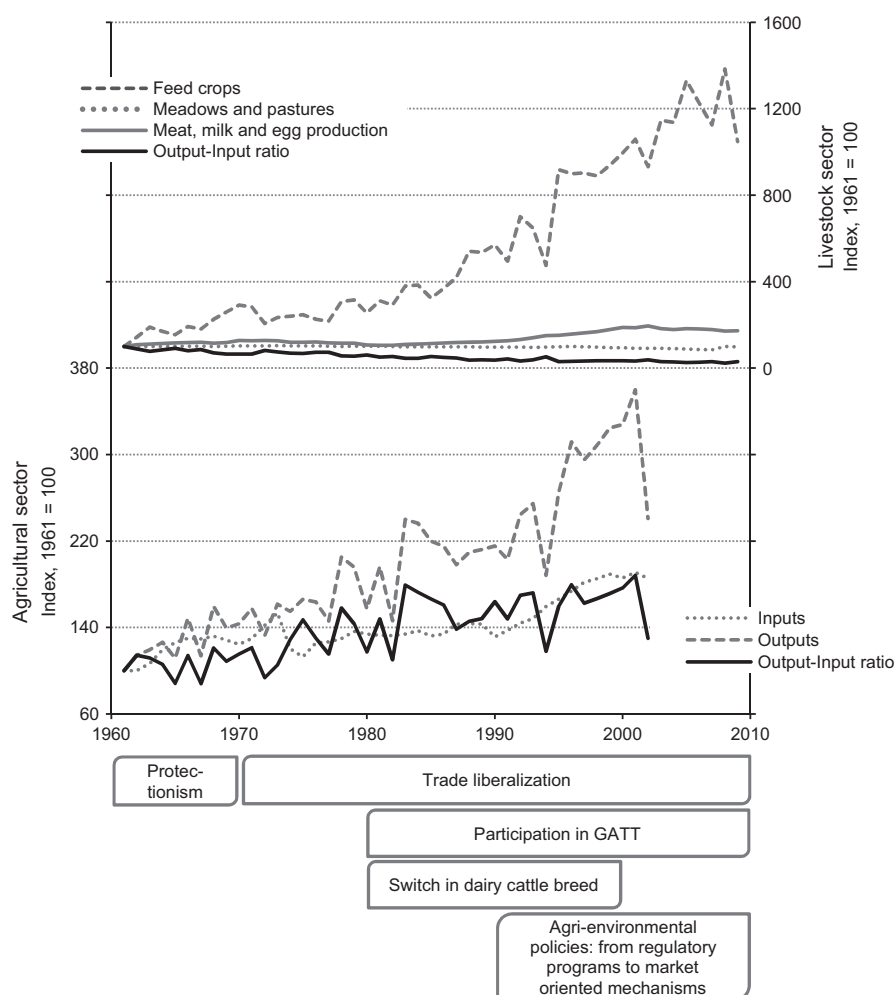
Until the 1990s, agricultural policies were led by socio-economic objectives. Since the 1990s, more emphasis has been put on sustainable agricultural development (Stringer and Anderson 2002). Current agricultural policies aim to improve market responsiveness, and encourage sustainable agricultural practice (i.e., approaches that combine economic, environmental, and social aspects). Projects also focus on food quality. Agri-environmental policies concentrate on water, soil erosion, salinity, and biodiversity loss (Stringer and Anderson 2002). Measures to achieve this include research, education, voluntary adoption of best practice, and development of guidelines in

collaborations between governments, NGOs, industries, and communities. Over time, regulatory approaches have been complemented, or even substituted, with market oriented mechanisms like for example the polluter pays principle. The basis of these measures is that prices reflect social costs and benefits, that is, positive and negative externalities are taken into account (Stringer and Anderson 2002).

### Yield developments

In Australia, a small average change in wheat and rice yields between 1961 and 1980 was followed by a significant increase in the 1980s (Fig. 3 and Table 1). As this coincides with the participation in the General Agreement on Tariffs and Trade (GATT) after 1979, it is likely that the improvements are a result of the trade policy reforms which opened the international market (Anderson *et al.* 2009). Notably, the input use levels remained stable. Thus, it seems that the reforms motivated farmers to use their resources more efficiently, which resulted in higher production levels and improved productivity in the early 1980s (Fig. A1). Agri-environmental policies were first implemented in the 1990s and aimed to improve market responsiveness and encourage sustainable agricultural practice (Stringer and Anderson 2002). Since their introduction, agricultural production has further increased. But, fertilizer use and irrigation levels increased as well and the productivity of the agricultural sector did not improve compared to the 1980s (Fig. A1). Also, wheat and rice yields stagnated in the 1990s. Sugarcane yields have been relatively steady and did not significantly improve in the 1980s. A considerable drop in yield in the period 1990–92 was followed by a peak in the second half of the 1990s and another plunge in 2001–02 due to drought. Then, sugarcane yields seem to have stabilized again around previous levels.

Beef and milk yields have almost continuously improved, except for a period of stagnation in the 1970s and early 1980s (Fig. A9 and Table 1). In this period of market reforms, also the production and export of beef and milk temporarily declined (FAOSTAT). Between 1980 and 2000, beef and milk yields improved while their export markets grew, feed crop consumption increased enormously (Fig. A1), and a shift in dairy cattle breed from British breeds to Holstein–Friesian animals was made (Trewing 2004; Doyle and Stockdale 2011). Although the majority of cattle production is still extensive, the rise in feed crop consumption is likely to be related to the intensification of beef production in South Australia and the expansion of feedlot-based dairying (Pink 2012). The above findings suggest that the development of export markets has been an important driver for changes in the production systems



**Figure A1.** Australian agricultural and livestock productivity developments and institutional, economic and technological/management developments. (GATT, general agreement on tariffs and trade).

of beef and milk, and all these factors together have contributed to yield improvements. Due to the massive increase in feed crop use, however, the output–input ratio of the livestock sector has decreased significantly. The decline has slowed down since the mid-1990s, which may be related to the introduction of agri-environmental policies.

## Appendix 3

### Brazil

#### Agricultural characteristics

Agriculture in Brazil is characterized by concentrated land ownership; medium- and large-scale commercial farms contribute the bulk of agricultural output (Anderson and Valdés 2009). Crop and livestock are combined in mixed

farming systems (Dixon et al. 2001). The majority of cattle is held in *extensive mixed* (rain-fed) production systems (Wint and Robinson 2007). These are found in the wooded and open savannah areas (the Cerrados) in the Central West of Brazil, and also in the Southeast (Dixon et al. 2001; Cederberg et al. 2009). Extensive ranching is the primary activity, but cultivation of soya and corn is increasing. In addition to this farming type, *intensive mixed farming* takes place in Eastern and Central Brazil. This system produces most of the sugarcane, which is mainly cultivated in the Central South of Brazil. *Dryland mixed farming* (which is mainly semisubsistence farming) is the major system in northeastern Brazil (Dixon et al. 2001).

A significant expansion of the agricultural sector in the last decades was accompanied by a considerable increase in deforestation, replacement of native vegetation, and biodiversity loss (Martinelli et al. 2010; Ferreira et al. 2012). Also, the use of fertilizers and other inputs, and the ruminant density on meadows and pastures have risen



significantly since the 1970s (Figs 2 and A10). The ruminant density in Brazil is high compared to the other selected countries, except to India. The largest share of the cattle population is being held for beef production; about 10% are dairy cows (Cederberg *et al.* 2009; FAOSTAT). Beef and milk production are mainly based on extensive systems, in which cattle grazes on pastures all year round (Cederberg *et al.* 2009). In the emerging semiextensive systems, herds also receive supplemental feed from crops and various concentrates. Feedlot-based, intensive systems are still rather uncommon (Cederberg *et al.* 2009).

### Economic and institutional developments

Prior to 1950, the Brazilian market was concentrated around the export of food and raw materials, and the import of industrial products (Baer 1972). Between 1950 and the mid-1970s, the focus shifted to national industrialization, and policies aimed at replacing foreign imports with domestic production (Carvalho 1991). This is called Import Substitution Industrialization (ISI) (Carmo Oliveira 1986). To protect the industry, wage rates were kept low by restrained food prices (Carvalho 1991). In order to realize low food prices, Brazilian agriculture was heavily and increasingly taxed (Carmo Oliveira 1986). Levies consisted partly of direct export taxes, but were dominated by indirect taxation resulting from industrial protection policies (Anderson and Valdés 2009). Due to the industrial protection, also input prices increased. Therefore, the government provided credit and fertilizer subsidy to promote the use of fertilizer and other inputs (Carvalho 1991).

Trade liberalization started in the 1980s, and continued to the mid-1990's (Anderson and Valdés 2009). Reforms included the removal of import and export restrictions, and the redistribution of resources from import-competing to export-oriented sectors (Anderson and Valdés 2009). This transformation took also place in the agricultural sector (Anderson and Valdés 2009). Today, major exports of agricultural products like soybean, sugar, beef, and ethanol contribute to Brazil's positive balance of trade. Thus, the agricultural sector plays an important role in the economic development of Brazil (Martinelli *et al.* 2010; Ferreira *et al.* 2012).

During the last years of industrial protectionism, the oil crisis in 1973 prompted the Brazilian government to phase out fossil fuels. The ProÁlcool program was launched to promote the sugarcane industry and bio-ethanol production (Stattman *et al.* 2013). Blending ethanol to fossil fuel was already introduced in 1931, but the ProÁlcool program brought about a major increase in ethanol consumption and production (Stattman *et al.* 2013). Today, most of the ethanol produced is still intended for the

domestic market. In 2009, almost 14% of the production was exported (Lamers *et al.* 2011). To improve Brazil's energy diversity and independence, a second biofuel program was implemented in 2004: the National Program of Production and Use of Biodiesel (PNPB). Due to the abundance of soy and the search for new soy markets, biodiesel production is largely based on the conversion of soybean oil (Stattman *et al.* 2013).

The need to control deforestation was already recognized in the 1920s. The first Forestry Code, which dates from 1934, regulated the conservation of forests on private land (Banerjee *et al.* 2009). In 1965, a second code expanded the land dedicated to preservation from forests to other sensitive areas. Also, it created conservation areas outside the private rural properties (Banerjee *et al.* 2009). Due to economic priorities, however, enforcement of the codes was weak. Between 1974 and 1987, when the focus shifted from protectionism to trade liberalization, the government promoted livestock production, forestry, and mining in the Brazilian Amazon (Banerjee *et al.* 2009). The markets for Brazilian beef have been growing since the 1970s and led to considerable expansion of extensive cattle ranching on cleared forest land in this region (Bowman *et al.* 2012). In addition, the more recent expansion of soy production on previous pastures causes further expansion of cattle ranching into the Amazon (Bowman *et al.* 2012). Policies and other initiatives that aim to intensify cattle production are in early stages yet (Bowman *et al.* 2012).

### Yield developments

In Brazil, the developments in the yield of corn and soybeans are comparable. From the 1960s to 1980s, yield growth rates were moderate and highest in the 1970s (Fig. 3 and Table 1). In the 1990s, high improvement rates of more than 3.5% year<sup>-1</sup> were attained (relative to 1991). Fertilizer use increased substantially in the late 1960s and the 1970s, declined and stagnated in the 1980s and increased again in the 1990s (Fig. 2). Thus, it appears that fertilizer subsidies provided during industrial protection (1950s–70s) (Carvalho 1991) led to an increase of fertilizer use and of yields, especially in the 1970s. The economic reforms in the 1980s (Anderson and Valdés 2009) temporarily hindered agricultural development, but the opening of agricultural export markets stimulated further improvements in the 1990s. Notably, after agricultural productivity declined in the 1960s and 1970s, the output-input ratio has remained fairly constant from the 1980s until 2002 (Fig. A2). Despite the introduction of the biodiesel program in 2004 (Stattman *et al.* 2013), soybean yields stagnated in this decennium. Yet, the share of soybeans used for biodiesel production has been rather small in the first years (0.5% in 2006 compared to 12% in 2010) (Barros



2013; FAOSTAT). The development of sugarcane yields is similar to the trend for corn, but the first period of major growth is found between 1975 and 1985. This is clearly related to the introduction of the PróAlcool program in the early 1970s (Stattman *et al.* 2013). Tractor use and irrigation also grew significantly after 1973, thus are probably related to the rise of sugarcane production.

Considering beef and cow milk production, no significant yield improvements were attained from 1961 until the 1980s (Fig. A9 and Table 1). This period of relatively stable yields was interrupted by a few years of decline in the mid-1970s. Major yield increases were only attained in the early 1990s. This suggests that the promotion and expansion of cattle ranching during the period of liberalization (Banerjee *et al.* 2009; Bowman *et al.* 2012) did not directly stimulate yield improvements. Only when the export markets were fully opened in the early 1990s, yields significantly improved. For milk, this growth continued

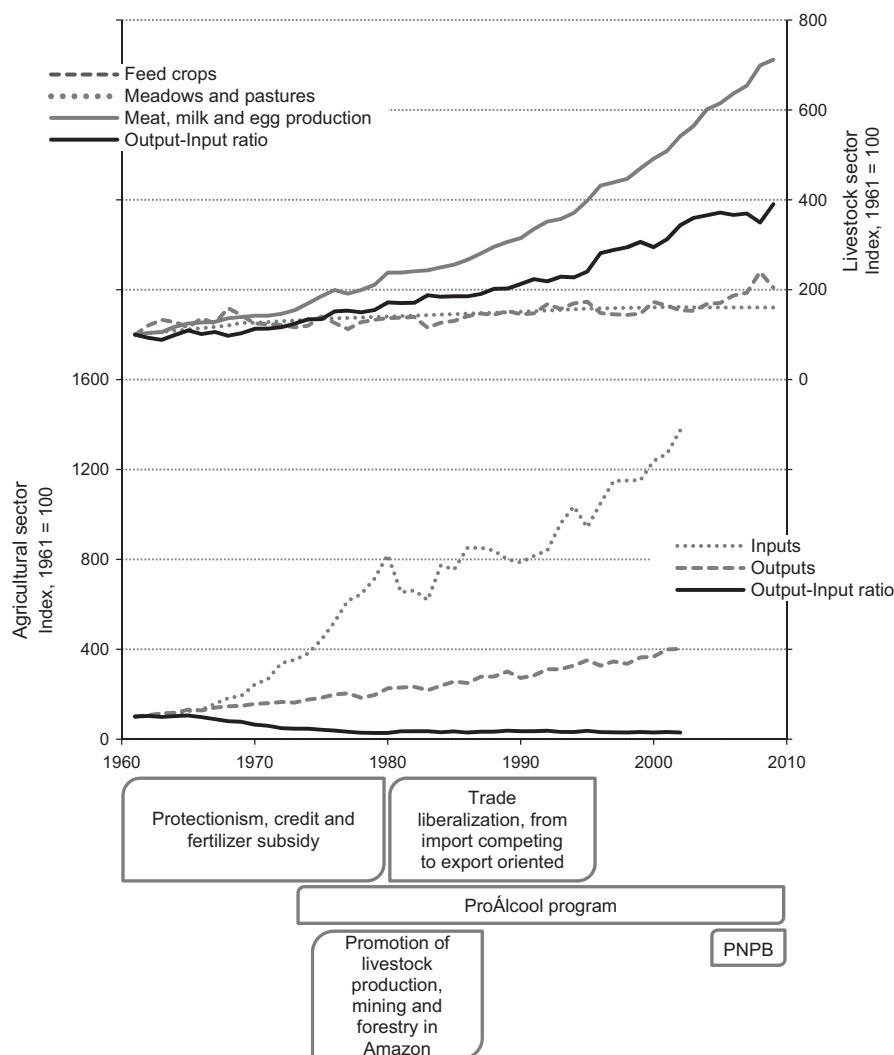
in the late 1990s and 2000s, but at a lower rate. The initial increase in beef yields was first followed by a decline in the late 1990s, before yields increased again in the 2000s. As the production of beef and milk has grown significantly faster than the use of feed crops and the area of pasture land, the output–input ratio of the livestock sector has continuously increased over the past five decades, especially since the mid-1990s (Fig. A2).

## Appendix 4

### China

#### Agricultural characteristics

Agriculture in China is characterized by large environmental diversity, and large diversity in agricultural products.



**Figure A2.** Brazilian agricultural and livestock productivity developments and institutional, economic and technological/management developments (PNPB, National Program of Production and Use of Biodiesel).

The Qinling mountains divide China into water-deficit (North, West) and water-surplus regions (South, Northeast) (Veeck et al. 2011). There are four major farming systems (Dixon et al. 2001). *Lowland rice production* is found in humid and moist sub humid areas in South and Central East China. Rice production is rain-fed, with supplementary irrigation where available. Important livelihoods are, besides rice, subsidiary crops like corn and soybeans, livestock, and off-farm work. *Upland Intensive Mixed Farming* is found in upland and hill areas with humid and subhumid climate (South East and North China). A significant area, mainly rice, is irrigated. Livestock contributes to draught power, meat, income and savings. Also off-farm work is an important income source. *Temperate mixed farming* is found in moist and dry subhumid areas in Central Northern China. The major crops are wheat and corn. Livestock is also an important livelihood.

*Pastoral farming* is located in semiarid and arid temperate climates in Western China. Pastoralism is based on extensive grazing of mixed herds (camels, cattle, sheep and goats) on native pasture. In local suitable areas, farmers apply irrigated crop production (e.g., cotton, barley, wheat). Characteristic for the agricultural sector of China are the majority of small-scale farms and the application of multiple cropping systems, that is, the production of more than one crop per year on the same land (Veeck et al. 2011).

China aims to be largely self-sufficient in grain production. Because of its large population, land availability for agricultural production is an important issue (Veeck et al. 2011). Economic growth has caused a major increase in population and demand for housing, transport, and industry in the Eastern coastal area. Much land in this region, however, is fertile and highly productive agricultural land which is lost due to the urbanization process (Karplus and Deng, 2008a; Veeck et al. 2011). Due to this pressure, even marginal lands (e.g., with very limited precipitation or extreme slope) are cultivated (Veeck et al. 2011).

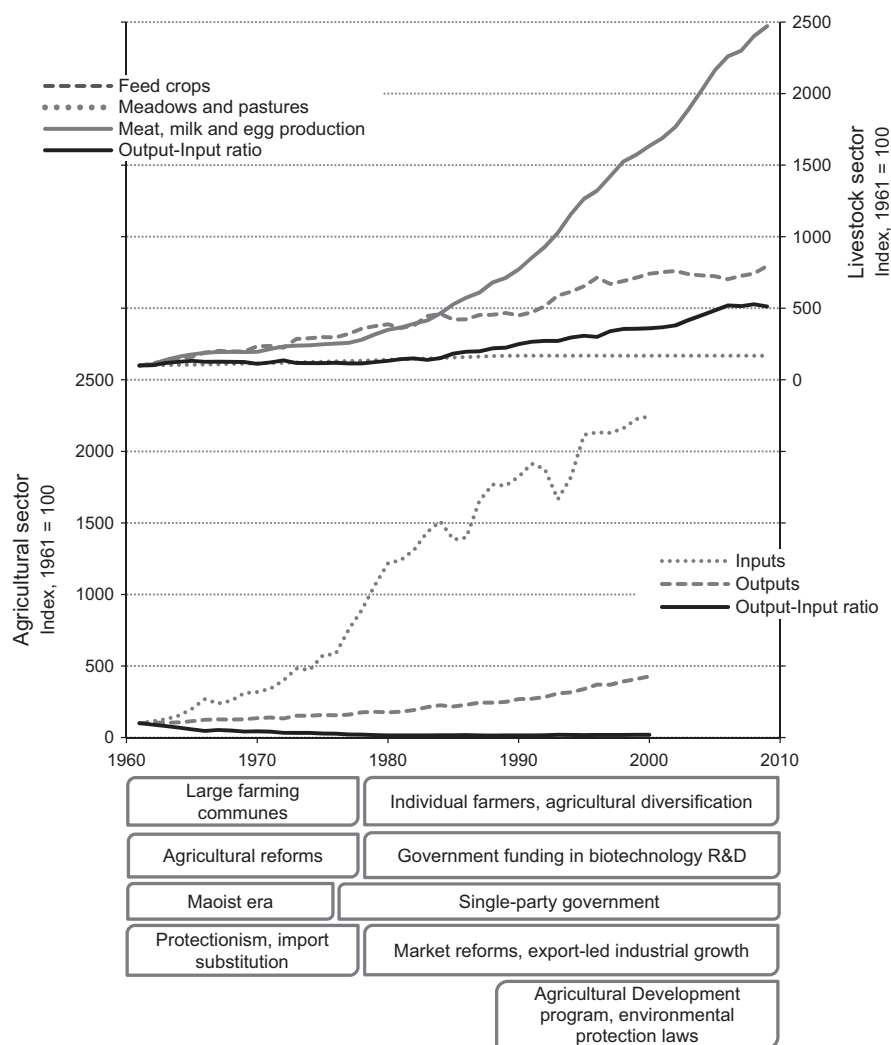
Without irrigation, the dry areas are of marginal use for intensive agriculture. Water shortages hamper the improvement of agricultural production in these regions. Therefore, irrigation has expanded at a high rate (Fig. 2). This, however, is causing severe water shortages as water consumption outpaces replacement through precipitation; there are major concerns that groundwater reserves are being depleted, especially in arid areas in Eastern and Western China (Karplus and Deng, 2008a; Veeck et al. 2011). Fertilizer use has increased dramatically in the past five decades (Fig. 2). Fertilizer use is especially high in lowland rice and in temperate mixed farming systems (Dixon et al. 2001). The overuse of fertilizers is associated with land degradation, air pollution, and eutrophication of water sources (Veeck et al. 2011).

## Economic and institutional developments

The period from 1949–1976 in China is called the Maoist era. During this era, the Chinese Communist Party (CCP) was in power. Governance was characterized by a strong inward orientation and self-imposed isolation (Veeck et al. 2011). Also, policies were relatively homogenous for the nation as a whole, and the use of capital and resources was regulated centrally (Veeck et al. 2011). In this era, farming took place in large farming communes (Tauger 2011). These communes were difficult to manage. In 1959, this caused a collapse of farm production and a huge famine. In order to solve the problems, agricultural reforms were introduced which included the reparation and construction of irrigation systems and the distribution of high-yield seeds (Karplus and Deng, 2008a; Tauger 2011). Programs to develop improved crop varieties had already started in the early 1950s. The communes were broken up when the market reforms started in 1978. Since then, individual farmers have been leasing land from the local authorities. The resulting diversification of crop production and farmers' activities, income, and education level became visible in the second half of the 1990s (Veeck et al. 2011).

Since the end of the Maoist era, the CCP has still been in charge. The central government continues to play an important role in planning and guiding the direction of development (e.g., economic decision making), but the role for local governments is increasing (Veeck et al. 2011). Also, from 1978, the focus of the market shifted from import substitution industrialization toward export-oriented development strategies (Anderson and Martin 2009). This resulted in an export-led industrial growth, and also a restructuring of the economy away from agriculture and heavy industry toward light manufacturing and service activities (Anderson and Martin 2009; Veeck et al. 2011). The taxation of agricultural exports has been reduced, but the protection of import-competing agriculture, especially of rice, has been increased (Anderson and Martin 2009). Because of the importance of the agricultural sector, the government increased investments in agricultural R&D and started to fund research in biotechnology. This support was continued in the following decades (Karplus and Deng, 2008b).

Environmental protection laws were first introduced in the late 1980s. These laws aimed to prevent the loss of high-productivity cropland caused by the expansion of urban and industrial areas in Eastern China (Veeck et al. 2011). Also, the increased awareness about environmental problems and the need for more efficient agriculture led to the implementation of the Comprehensive Agricultural Development (CAD) program in 1988 (Veeck et al. 2011). The CAD program was introduced because of the low productivity of a large share of arable land and increasing grain imports. The program aimed to enhance the quality



**Figure A3.** Productivity developments in the Chinese agricultural and livestock sector and institutional, economic and technological/management developments.

of agricultural land through better land management, including improved fertility and drainage, balanced use of inorganic fertilizer, irrigation and water storage and conservation. The CAD still exists (Veeck et al. 2011).

### Yield developments

Since the agricultural reforms in the early 1960s (Karplus and Deng, 2008a; Tauger 2011), irrigation, fertilizer use, and mechanization have been increasing almost continuously (Fig. 2). In addition, fast yield growth is found for all crops (corn, rice and wheat), Table 1. On average, the average yield growth rate was the highest for wheat (1.8% year<sup>-1</sup> relative to 2010), but the highest absolute improvement was achieved by corn and rice (93 kg ha<sup>-1</sup> year<sup>-2</sup>). These considerable gains can mainly be attributed to the introduction of new technology, which was realized by significant public investments in

infrastructure and research (Karplus and Deng, 2008a). In the 1990s, however, yield improvements dropped. This may reflect the diversification of farmers' crop production after the economic reforms (Veeck et al. 2011). In the following decade, the growth rates of corn and wheat yields increased again, while rice yield improvements continued to slow down.

The yield growth rates for beef and milk have been lower than for crops. This may be explained by the major importance of cattle for delivering draught power, as agricultural production is still labor-intensive in China (Fig. 2). The market reforms may have resulted in some improvements in cattle production; the beef and milk yield shortly increased around the 1980s. Afterwards, beef yields stabilized again. Milk yields also stagnated for some years, but have been increasing at a rate of 3.5% year<sup>-1</sup> since the late 1990s (relative to 2001, Fig. A9 and Table 1). At the same time, the consumption of milk and dairy products

by urban residents soared, which was caused by China's growing prosperity (Bao 2011).

After the output-input ratio of the agricultural sector had declined rapidly in the 1960s and 1970s, it stabilized in the 1980s and improved gradually in the 1990s (Fig. A3). It is likely that both market liberalization and agri-environmental policies, which aim to improve agricultural land quality (Veeck *et al.* 2011), have contributed to this reversal of the downward trend in productivity.

## Appendix 5

### India

#### Agricultural characteristics

India has two major farming systems: rice-wheat and rain-fed mixed. The rice-wheat system in Northern India is characterized by wetland rice production in summer (monsoon season), and irrigated wheat production in winter (cool, dry season). A significant amount of livestock is held in this system, where bovines produce draft power, milk and manure for composting (Dixon *et al.* 2001).

The rain-fed mixed system occupies the largest area in India (Central and Southern India). It is mainly rain dependent, but according to Dixon *et al.* (2001), about 16 percent of the area cultivated under this system was equipped with simple, small-scale irrigation techniques around 2000. Infrastructure and market access are poor, and agricultural activities are oriented toward subsistence. The main livelihoods are cereals, legumes, fodder crops, livestock and off-farm activities (Dixon *et al.* 2001).

The input-intensity of the agricultural sector has increased substantially since 1961 (Fig. 2). Yet, as the increase in input use outpaced the growth in total production, the output-input ratio has declined seriously (Fig. A4). This has caused major environmental issues. Large-scale irrigation in Northern India has inflicted soil salinization and groundwater depletion (Shah 2012). Also, groundwater is polluted due to intensive use of fertilizers and rudimentary processing of livestock wastes. In addition, large livestock populations cause soil degradation through the conversion of natural vegetation (Shah 2012). In Southern India, soil erosion is the main problem. The vegetative cover and organic matter content of soils are low. Yet, farmers continue to cultivate crops on marginal lands to meet their basic needs (Shah 2012).

#### Economic and institutional developments

India is a former colony of the United Kingdom and gained independence in 1947. In order to prevent famines,

and to ensure affordable prices for basic foods, the Indian government has been intervening in the food market since its independence in 1947. In the public distribution system, which was established in 1958 and is still present, basic foods are sold at subsidized prices (Gulati and Pursell 2009).

In response to droughts and famines in 1965–66, policies aimed at food grain self-sufficiency and agricultural imports began to be replaced by domestic production (Gulati and Pursell 2009; Tauger 2011). Green revolution technologies played an important role, as the government implemented many programs to modernize agriculture at a high speed. This included the development and planting of high-yielding wheat and rice varieties and large subsidies for electricity and fertilizers (Gulati and Pursell 2009; Tauger 2011). According to Dixon *et al.* (2001), however, agricultural development during India's Green Revolution did mainly take place in 10 percent of India's districts which had adequate local infrastructure for water management, transport and electricity (for tubewells). In the 1970s and early 1980s, the import of edible oils expanded significantly. This led to policies which aimed to decline these imports and substitute them with domestically produced oils (Gulati and Pursell 2009). Import substitution was abandoned in the 1990s and the focus shifted to an export oriented economy. Trade policies were reformed through the structural adjustment program (SAP), which was introduced 1991 (Mukherjee and Chakraborty 2012).

A significant number of environmental policies exist that aim to control the use and management of natural resources. Enforcement of these regulations, however, is weak (Shah 2012).

#### Yield developments

In India, crop yields have almost continuously grown in the last five decades, but at different rates. The highest rates are found for wheat and rice in the period 1961–1990 (Table 1). Explanations for these achievements can be found in the major investments by the government in the modernization of agriculture (in Northern India), the development and adoption of high-yielding rice and wheat varieties and agricultural subsidies (Dixon *et al.* 2001; Gulati and Pursell 2009; Tauger 2011). After 1990, the absolute and relative yield growth of these crops has decreased. Soybean yields started to increase in 1972. This coincides with the introduction of the import substitution policy for edible oils (Gulati and Pursell 2009). Since 1961, sugarcane yields have increased at a moderate rate until 1999. After a decline in 2000–2004, yields returned to the level of the mid-1990s. For all crops, there is no clear relation between market reforms and yield developments in the 1990s. Although the linear regression data

suggest that yield growth of rice, wheat and soybeans slowed down in this decade, the graphs in Figure 3 do not show a significant deviation from an earlier trend which can be linked to the liberalization process.

Regarding cattle product yields, there is a significant difference in developments between milk and beef. Cow milk yields have increased all five decades, and growth rates increased as well. Similar to China, this is likely to be related to increased milk consumption (FAOSTAT). Beef yields are low compared to the other six countries. This is likely to be related to the protected status of cows in Hinduism, the major religion in India. Beef yields have been rather constant and only increased in the 1970s and 1980s. This temporary improvement may be explained by reduced need for draft power due to the mechanization process (Fig. 2). Mechanization, however, has continued in 1990s, but this is not reflected in further improvement of beef yields.

Due to the enormous increase in inputs, the agricultural productivity has continuously decreased between 1961 and 2000 (Fig. A4). Although the decline has slowed down, the lack of productivity improvements confirms the weak

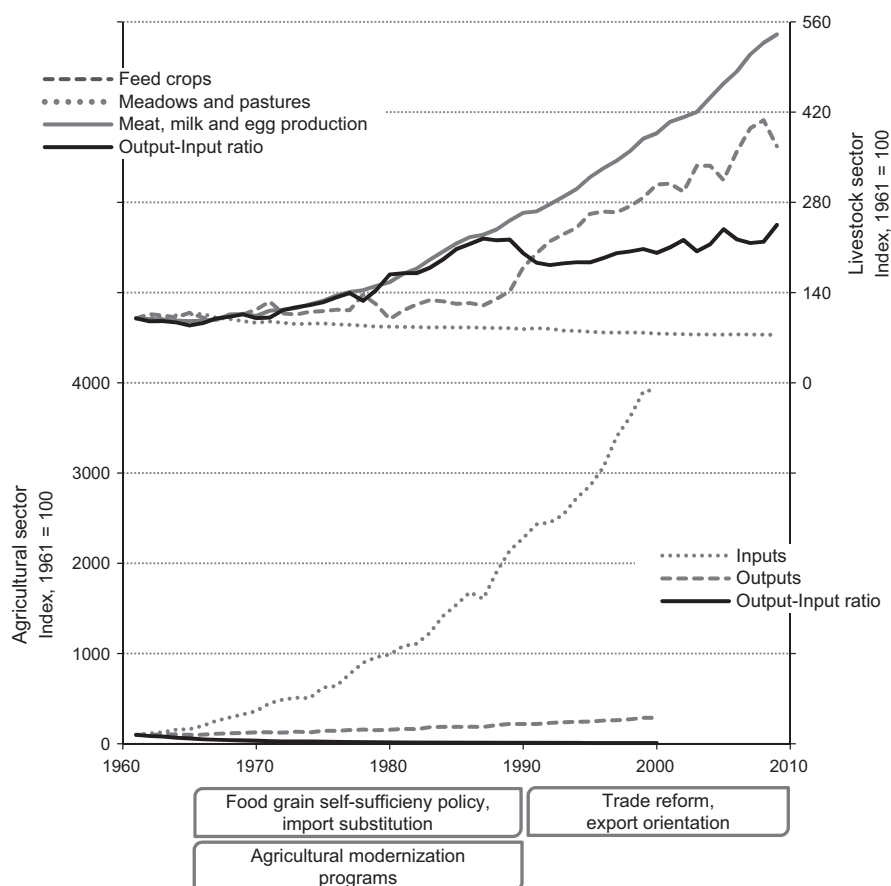
enforcement of agri-environmental policies in India (Shah 2012).

## Appendix 6

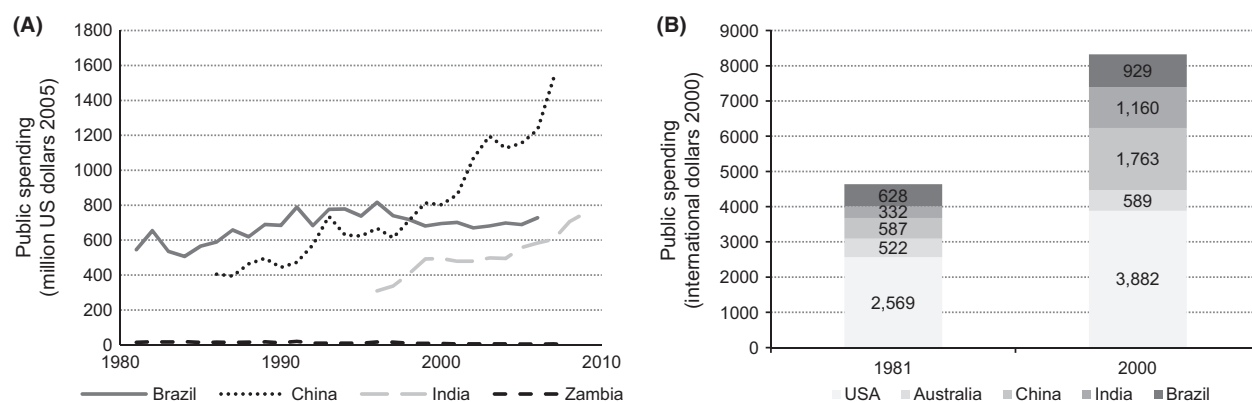
### USA

#### Agricultural characteristics

In the United States, agricultural production is mainly concentrated in the Pacific and Central (Midwestern) regions and the Southern plains (Alston et al., 2010a). Over the past decades, the total number of farms in the United States has declined but the number of large scale farms has increased. Still, large-scale farms are a minority of all US farms, but they produce more than two-third of agricultural output (Anderson and Valdés 2009; Alston et al., 2010a). The production practices depend on the farm size and the natural resource base (e.g., soil moisture and fertility). For example, the major practice in the corn belt (Midwestern USA) is dryland farming. In the Central



**Figure A4.** Productivity developments in the Indian agricultural and livestock sector and institutional, economic and technological/management developments.



**Figure A5.** Public agricultural R&D spending: (A) Historical progress in spending in developing countries (ASTI Data Tool version 1.1); (B) Spending in OECD and developing countries (Alston et al., 2010b).

valley of California (Eastern USA), irrigation is applied (Carpentier and Ervin 2002).

The agricultural production of the last five decades can be characterized by intensive management, especially with regard to mechanization (Fig. 2). It seems, however, that the intensity of input uses has stabilized since the 1970s and 1980s. Also, the ruminant density on pastures has declined (Fig. A10). In the livestock sector, dairy production is mainly confinement based (McCormick 2011). Pasture use, however, has grown since the early 1990s (McCormick 2011). In pasture based production systems, dairy cows may be at pasture during parts of the year. At the same time, and in winter months, they receive stored forage along with varied levels of supplemental concentrates throughout the year (McCormick 2011). Beef production is mainly characterized by cow-calf herds on pasture and (winter) hay (Pelletier et al. 2010). Beef cattle are finished in feedlots where they receive a mixed, high concentrate feed ration. Less than 1% of beef cattle are finished in pastures (Pelletier et al. 2010). On pastures, no housing is provided for cow-calf herds. Hormone implants are employed in the feedlot stage. Calves can also be sent to feedlots directly. Pelletier et al. (2010) mentions that this is common practice in the US Upper Midwest.

The high intensity of agricultural management in the United States has led to a wide range of environmental issues. The most important problems are soil erosion (i.e., loss of the fertility and water-holding capacity of the soil) and contamination of water sources by agricultural chemicals and livestock manure (Carpentier and Ervin 2002).

### Economic and institutional developments

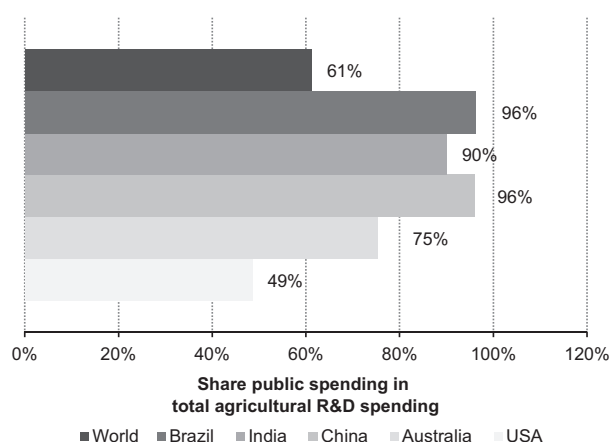
From their introduction in the 1930s, agricultural policies in the United States have been differing significantly in composition from the EU and other OECD countries. The

focus of agricultural policies has been on providing food aid and nutrition assistance. Assistance to farmers in the form of commodity support programs is placed second (Silvis and van Rijswijk 2002). These commodity programs consisted of price support and direct income payments (Silvis and van Rijswijk 2002; Blandford and Boisvert 2006). To limit payments by the government, crop programs, such as corn and wheat, placed limits on production. For other commodities, like milk, import restrictions were applied (Blandford and Boisvert 2006). Market liberalization and multilateral trade agreements have changed the programs for farm support. Since 1985, income support has shifted to payments that are decoupled from prices and production. Also, production limitations have been replaced by more planting flexibility, enabling farmers to make market-based decisions (Blandford and Boisvert 2006).

The United States have been dominant in agricultural R&D expenditures (Alston et al., 2010b). For example, Figure A5 shows that American public spending in 2000 was twice as high compared to the investments made by China. In addition, agricultural R&D in the United States has been funded extensively by the private sector. The public and private sector contribute both about half of the total investments (Alston et al., 2010b). In other countries, especially the developing countries, the share of private spending has been much smaller (Fig. A6). In addition, innovations in agricultural technology have been stimulated by intellectual property rights. Until the 1970s, however, this protection excluded inventions related to living organisms like plants and animals (Alston et al., 2010c). This changed in the 1980s and the legalization of patents on life forms cleared the way for biotechnology to rapidly expand (Alston et al., 2010c).

Agri-environmental policies in the US have been implemented from about 1970 (Carpentier and Ervin 2002). Traditionally, broad programs were implemented in each state. More recently, individual state and local programs





**Figure A6.** Public share in total agricultural R&D spending in 2000 (Alston *et al.*, 2010b).

have emerged (Carpentier and Ervin 2002). The majority of agri-environmental policies have been voluntary-payment programs (Carpentier and Ervin 2002). The application of regulatory approaches which define input or performance standards for agriculture was limited by two factors. First, agriculture in the United States is characterized by a high variety in production practices and local circumstances (ecosystems, quality and sensitivity of resources). Regulation of this diversity in operations is technically difficult and expensive. Second, a strong agricultural lobby exists in the United States, and political influence on environmental protection has been modest (Carpentier and Ervin 2002). As a result, regulatory programs and environmental standards for agriculture have only been introduced since the second half of the 1990's. These regulatory programs focus on the quantity and quality of production inputs (especially water quality in livestock production, and pesticide use) (Carpentier and Ervin 2002). The most important environmental policies in the United States are the Conservation Reserve Program (CRP, farm bill 1985) and the Environmental Quality Incentives Program (EQIP, farm bill 1996). The CRP is a voluntary program that provides payments to farmers who apply conservation practices on environmentally sensitive lands (Silvis and van Rijswijk 2002). The EQIP provides financial and technical assistance to farmers to improve and protect the environmental quality of their properties (e.g., soil and water) (Silvis and van Rijswijk 2002).

### Yield developments

In the United States, the crop yield growth trends have been positive for most of the period 1961–2010 (Fig. 3). It is very likely that the substantial investments in agricultural R&D (Alston *et al.*, 2010b) have played an important

role in achieving these improvements. From the mid-1980s, growth of corn and wheat yields slowed down for about a decade. Probably, this deceleration is related to the reforms of trade and farmer support policies in the same period (Blandford and Boisvert 2006). Afterwards, however, absolute growth reached a record high in the 1990s (Table 1). For soybeans, growth accelerated in the 2000s. In addition to the effect of trade liberalization, these significant increases in yield growth may be attributed to the rise of biotechnology since the 1980s (Alston *et al.*, 2010c). Improvements in technology and management have also driven yield growth in beef and cow milk production. This technological progress is likely to be stimulated by investments in R&D and growing domestic milk consumption (Alston *et al.*, 2010b; FAOSTAT). Although absolute and relative yield growth of beef was highest in the 1960s, yields have also been increasing considerably since the mid-1980s after a period of stagnation in the 1970s. Cow milk yields have almost continuously increased and while the relative growth rate has been fairly constant, the absolute growth accelerated in the 1980s and 1990s.

Regarding agricultural management, tractor use peaked in 1966 and fertilizer use reached the highest level in 1980 (Fig. 2). Also, the output–input ratios of the agricultural and livestock have been improving since the 1970s (Fig. A7). As agri-environmental programs were introduced in the same decade, the developments in input use and agricultural productivity may well be related to these policies.

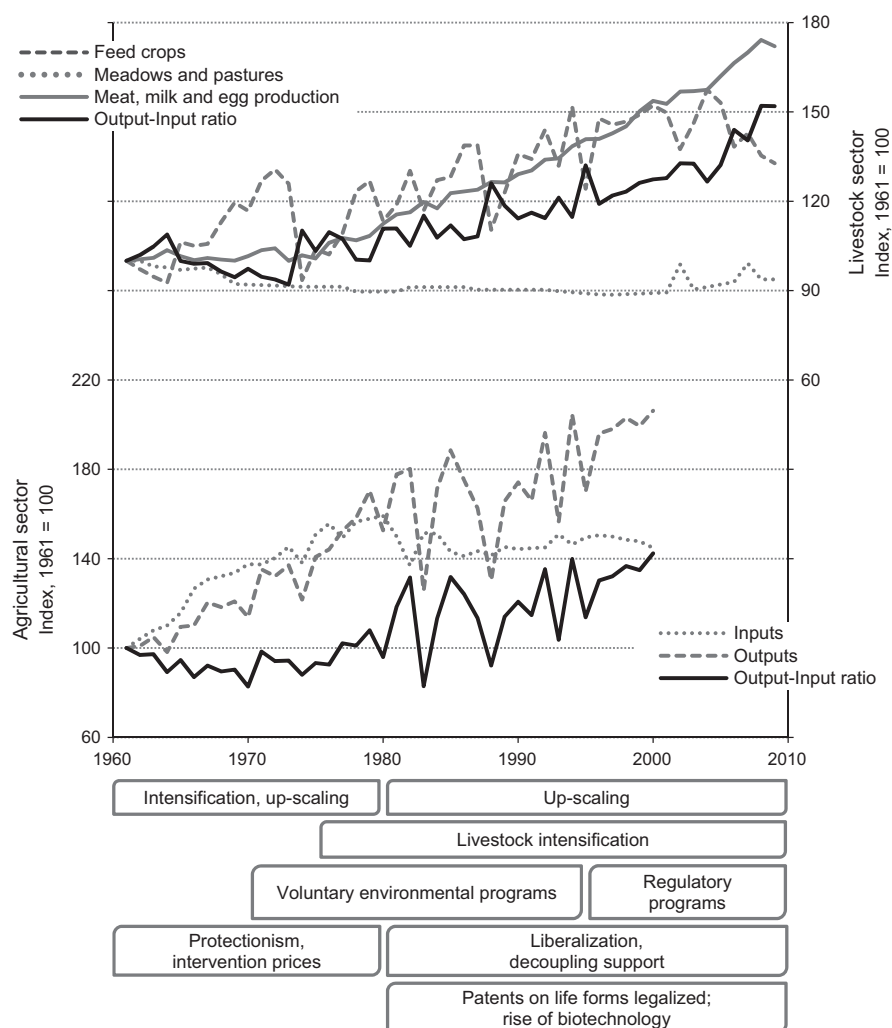
## Appendix 7

### Zambia

#### Agricultural characteristics

The agricultural sector in Zambia exists of a small number of large-scale commercial farmers who have good access to input and output markets, a few medium-scale commercial farmers for whom market access is difficult, and a majority of smallholders who are often engaged in subsistence farming (Howard and Mungoma 1996; Bonaglia 2009). The large-scale farmers produce and sell wheat, soybean, coffee, milk and other livestock products. Corn, however, dominates the agricultural sector and is mainly produced by the smallholders and medium-scale commercial farmers (Howard and Mungoma 1996).

The major farming systems in Zambia are maize mixed (Central and East Zambia) and cereal-root crop mixed (West Zambia) (Dixon *et al.* 2001). Maize mixed systems are found in plateau and highland areas with a dry subhumid to moist subhumid climate. Besides corn, principal livelihoods are tobacco, cotton, cattle, goats, poultry, and off-farm work.



**Figure A7.** Productivity developments in the American agricultural and livestock sector and institutional, economic and technological/management developments.

Cattle are kept for ploughing, milk, manure, but also for savings (Dixon et al. 2001). Cereal-root crop mixed systems are situated in regions of lower altitude and higher temperatures. The number of livestock per household is higher compared to the maize mixed system. The major sources of income are corn, sorghum, millet, cassava, yams, legumes, and cattle (Dixon et al. 2001).

In Zambia and other South African countries, the major environmental problem related to agriculture is declining soil fertility (Dixon et al. 2001). Soil degradation is caused by inappropriate management practices such as continuous cropping and overgrazing (Dixon et al. 2001). Average agricultural input levels in Zambia are low (Fig. 2).

### Economic and institutional developments

Zambia is a former colony of Britain (the region was named Northern Rhodesia) and gained independence in

1964. After independence, the economy heavily depended on copper exports and many people lived in the urban mining areas. To ensure food supply to these areas, the new government aimed to increase national corn production. In the colonial period, however, commercial corn production had mainly relied on large-scale European farmers. The new objective was to enhance the participation of smallholders in the commercial corn market (Howard and Mungoma 1996). The agricultural intervention system of price controls and subsidies, which also dated from the colonial period, was maintained. But, new pricing policies favored smallholders in remote areas over commercial farmers with good market access (Howard and Mungoma 1996; Pletcher 2000). In the early 1970s, agricultural policies were expanded with fertilizer subsidies, which mainly benefitted the corn sector (Howard and Mungoma 1996; Pletcher 2000). Both corn seed and fertilizer were made accessible to smallholder farmers in

remote areas through a network of cooperative depots. In addition, farmers could sell their corn to these depots (Howard and Mungoma 1996). In the meantime, the Zambian government had invested in a corn breeding program which resulted in the release of twelve new varieties between 1977 and 1994. The program was started in the early 1960s to reduce the import of crop varieties from Zimbabwe, on which European farmers had relied during the colonial period (Howard and Mungoma 1996).

Between 1973 and 1991, Zambia had been governed by single party rule. This period coincided with an economic crisis in the late 1970s and 1980s due to a collapse of the copper price in 1975 and poorly managed governmental interventions in the market (Pletcher 2000). Although attempts were made to reform (agricultural) policies in the 1980s, economic liberalization only started when a new government came to power in 1991 (Pletcher 2000; Jayne *et al.* 2003). Through liberalization, the corn market was fully privatized. But, intervention in the input markets for fertilizer and credit remained (Pletcher 2000). Fertilizer price subsidies had been eliminated in 1988, which resulted in high input costs for corn. Therefore, smallholders reduced their use of fertilizer and hybrid corn varieties and returned to the cultivation of traditional corn varieties and subsistence crops like sorghum (Howard and Mungoma 1996; Dixon *et al.* 2001). The government then decided to continue fertilizer distribution on loan, but this undermined the ability of the private market to distribute fertilizer commercially (Jayne *et al.* 2003). Also, underinvestment in infrastructure and other public goods had made the purchase of fertilizer unprofitable to many farmers (Jayne *et al.* 2003). In response to the reduced fertilizer use (Fig. 2) and corn production in the 1990s, a new policy for fertilizer distribution and subsidy (the Fertilizer Support Program) was implemented in 2002 (Djurfeldt *et al.* 2011).

Efforts to control soil erosion started in the mid-1980s, driven by the spreading problem of land degradation and the economic reforms in late 1980s and early 1990s. At first, commercial farmers adopted conservation farming technologies to improve the profitability of mechanized corn production (Haggblade and Tembo 2003). In 1995, appropriate technologies for smallholders were introduced as well. The development and promotion of the technologies was collectively conducted by farmer organizations, private companies, NGOs and the government (Haggblade and Tembo 2003).

## Yield developments

After corn yields declined and fertilizer use increased slowly in the 1960s, the introduction of fertilizer subsidies (Howard and Mungoma 1996; Pletcher 2000) caused these levels to

increase significantly in the 1970s (Fig. 2, Table 1). The fact that agricultural policies were mainly focused on corn production (Howard and Mungoma 1996; Pletcher 2000) is clearly reflected in the high yield improvement rate of 4.5% year<sup>-1</sup> for corn compared to 1.2 % year<sup>-1</sup> for soybeans and 0.1 % year<sup>-1</sup> for sugarcane between 1971 and 1990 (relative to 1971, 1973 for soy). After the elimination of fertilizer subsidy in 1988 due to economic liberalization (Howard and Mungoma 1996; Pletcher 2000), fertilizer use and corn yields declined in the 1990s. It appears that commercial farmers benefitted from the economic reforms, as irrigation levels increased considerably and soybean yields improved at a very high rate of almost 20 % year<sup>-1</sup> in the 1990s<sup>3</sup> (relative to 1991). Sugarcane yields increased at 0.7 % year<sup>-1</sup> in the same decennium. In addition, Figure A8 shows that the output-input ratio of Zambia's agricultural sector improved in the late 1980s and 1990s. Besides reduced fertilizer use, these advances in productivity may also be the result of the introduction of conservation farming technologies (Haggblade and Tembo 2003). After the adoption of the Fertilizer Support Program in 2002 (Djurfeldt *et al.* 2011), however, fertilizer use increased again, the area equipped for irrigation stabilized (Fig. 2) and overall agricultural productivity dropped. Corn yields rose again and sugarcane yields stabilized. The effect on soybean yields is unclear; after a steep decline in 2001 due to drought, yields recovered and returned to levels comparable to the 1990s.

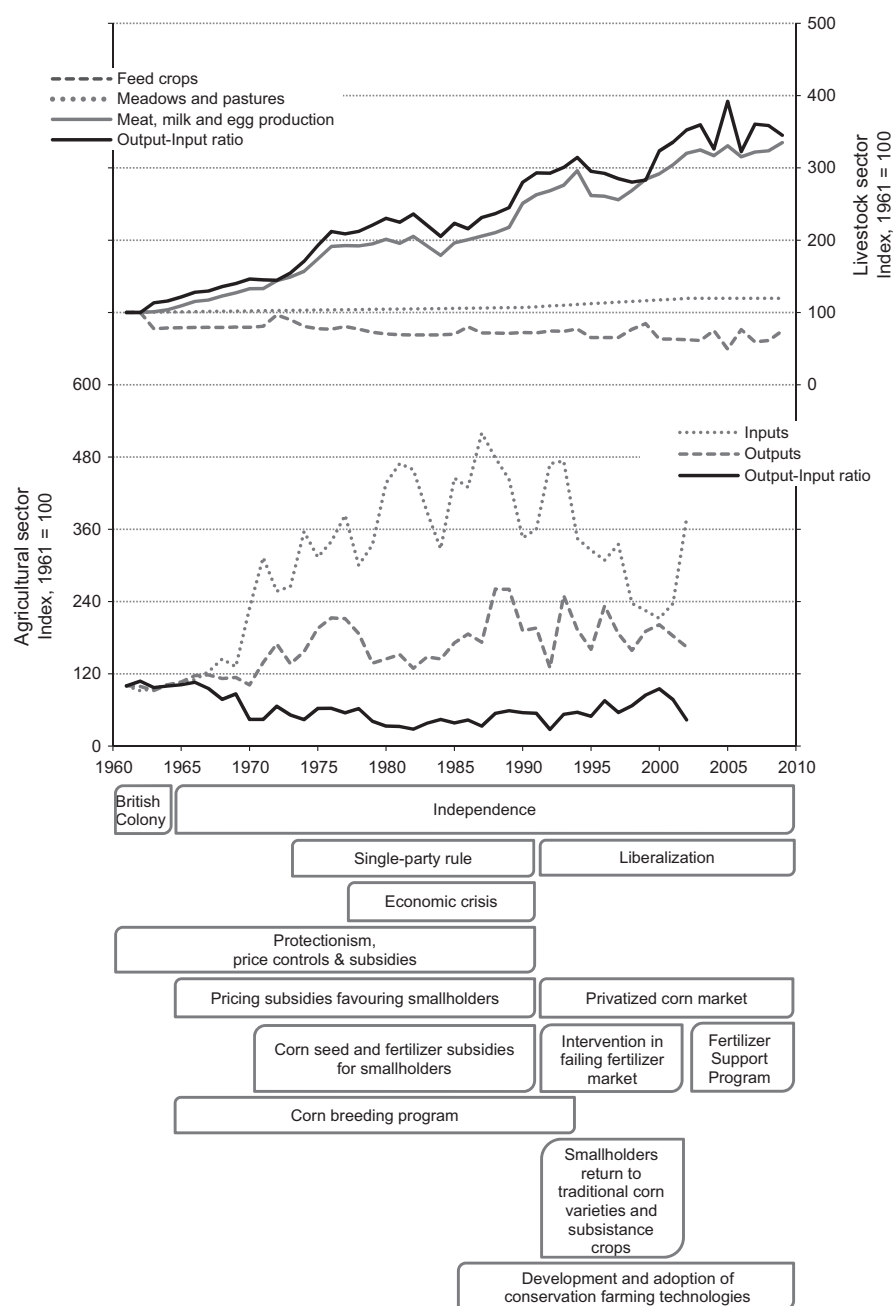
The FAO data show constant milk yields from 1961 until 2010. Beef yields have also been relatively stable, except for a decline of 1.8% year<sup>-1</sup> between 1968 and 1980 (relative to 1970). An explanation may be that the shift in focus of agricultural policies towards smallholders in this period has affected commercial farmers. This theory can, however, not be confirmed by statistics.

## Appendix 8

### Zimbabwe

#### Agricultural characteristics

Until 2000, the agricultural sector of Zimbabwe consisted of two major farming systems, which both occupied half of the arable land (Eicher 1995). The commercial farming system was dominated by a relatively small group of European farmers. These large scale farms were located in the higher rainfall areas in North-Eastern Zimbabwe (Whitlow 1985; Matondi, 2012c). Production was mainly focused on crops and input intensive (Whitlow 1985). The smallholder farming system involved a large number of African farmers. These small-scale farms were located



**Figure A8.** Productivity developments in the Zambian agricultural and livestock sector and institutional, economic and technological/management developments. Because of limited data, agricultural tractors are not included in the inputs and in the output-input ratio for the agricultural sector.

in the drier and more remote areas with poor market access. Farming included crop and livestock production and was mainly subsistence driven (Whitlow 1985).

From 2000, the Zimbabwean government acquired land from the European commercial farmers on a large scale. The land was divided into smallholder farms and commercial farms of varying scales, and redistributed to black farmers (Matondi, 2012a). Because of the limited knowledge and skills of the new farmers and poor access to inputs

and new technologies, the national level of irrigation and fertilizer use declined after 2000, see Figure 2 (Matondi, 2012b). Also, a loss of knowledge about livestock management led to more disease related deaths (Matondi, 2012b). As a result, the number of ruminants and the ruminant density on pastures declined (Fig. A10).

At the start of the 21st century, the major farming system was maize mixed (Dixon *et al.* 2001), see the description for Zambia. As more than half of the land

is not suitable for crop production without irrigation, cattle production plays an important role in Zimbabwe. The relatively high human and livestock populations and densities on marginal suitable lands, however, has resulted in large-scale soil degradation in smallholder farming areas (Whitlow 1988, 1985).

### Economic and institutional developments

Together with Zambia, Zimbabwe is a former colony of Britain (the region was named Southern Rhodesia). But, while Zambia was directly administered by the British during its colonization period, Zimbabwe was a self-governing colony. In 1965, The Zimbabwean government declared independence unilaterally, which was only recognized internationally in 1980. During the period of unilateral independence, the United Nations (UN) imposed sanctions on exports (Eicher 1995). To face these embargos, the government adopted a policy of import substitution (Marquette 1997). Policies aimed at agricultural diversification and commercial production of export oriented tobacco was replaced by cultivation of previously imported crops like corn, wheat and soybeans (Whitlow 1988; Eicher 1995). The period between 1965 and 1980 was also accompanied by a civil war, which was partly concerned with the uneven distribution of land between commercial farmers and smallholders (Whitlow 1985). Intensification of this guerilla in the late 1970s led to the abandonment of commercial farms in more remote areas and occupation by peasants (Whitlow 1988).

After independence in 1980, the government aimed to support the development of smallholders. A new land reform policy allowed the sale of commercial farmland on a 'willing buyer, willing seller' basis (Eicher 1995). In addition, smallholders were enabled to obtain credit to purchase seed and fertilizer and to make use of subsidized marketing services. This led to a rapid adoption of hybrid corn varieties (Eicher 1995). According to Eicher (1995), this successful smallholder green revolution in the first half of the 1980s could be realized because of good political, institutional, technological and economic conditions. An important factor to success was the investment in research, education and farmer support in previous decennia, which had already led to a green revolution by white commercial farmers in the 1960s (Eicher 1995; Langyintuo and Setimela 2009). Government financed research on high yielding crops in the 1970s and 1980s led to the release of more than 30 new hybrid corn varieties by 1990 (Langyintuo and Setimela 2009; Tauger 2011).

The success of the smallholder support system, however, resulted in high expenses for subsidies. In the late 1980s and early 1990s, the government lowered subsidies and encouraged farmers to diversify crop production (Eicher 1995). These reductions in public spending were part of an economic structural adjustment program (ESAP), which also included other measures to liberalize the economy (Marquette 1997). In addition, Zimbabwe's public R&D system slowly started to deteriorate; many European agricultural experts left Zimbabwe in the years after independence, while the shifted focus of agricultural research programs from commercial farmers to smallholders required experienced researchers (Eicher 1995).

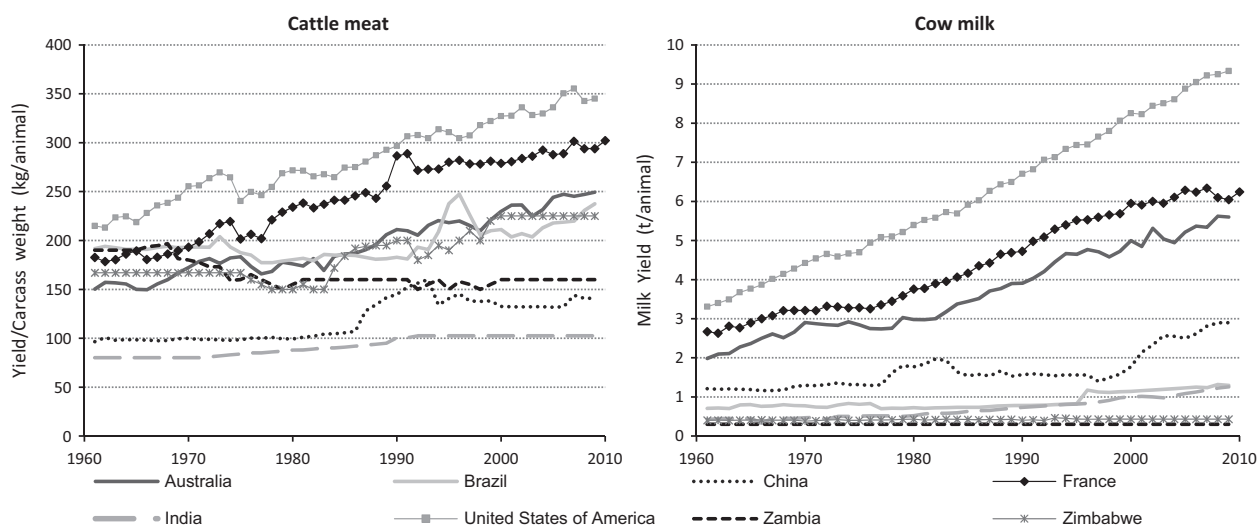
A series of events in the 1990s led to hyper-inflation and a collapse of the economy in the 2000s (Matondi, 2012b). The ESAP had seriously affected Zimbabwe's economy and the fast-track land reform program in 2000 disrupted commercial agricultural production. Also, beef exports to the EU were suspended because of foot-and-mouth disease (Marquette 1997; Matondi, 2012b). Due to this hyper-inflation, farmers' incomes dropped dramatically and inputs became unaffordable to many farmers (Langyintuo and Setimela 2009). While Zimbabwe was once called the bread-basket of South-Africa, now international support programs are needed to improve food security among impoverished rural households (Langyintuo and Setimela 2009). The program initiated by the British government in 2003 also aimed at promoting conservation farming practices (Langyintuo and Setimela 2009; Marongwe *et al.* 2012). The first agri-environmental policies, however, were already introduced in the early 20th century. The government provided significant financial support to apply conservation farming practices on commercial farms, which was very successful in the 1960s and 1970s (Whitlow 1988). Policies to address soil degradation in peasant farming had some success in the 1960s, but ceased in 1970s due to the political situation, increasing human and livestock populations, and a lack of (financial) support (Whitlow 1988). In the 1980s and 1990s, several research activities on conservation agriculture were initiated, but did not lead to significant uptake of conservation practices by smallholders (Marongwe *et al.* 2012).

## Appendix 9

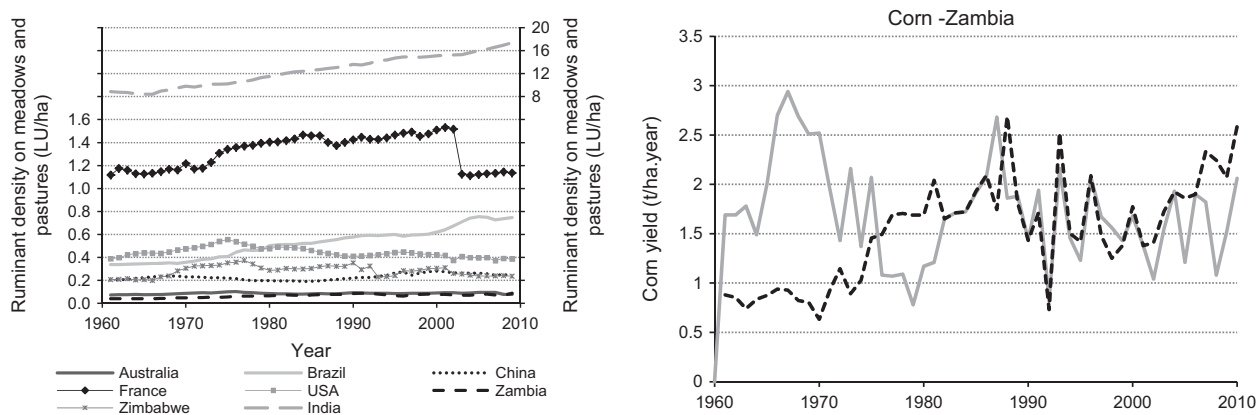
### Additional figures and tables

See Figures A9–A12 and Tables A1 and A2.

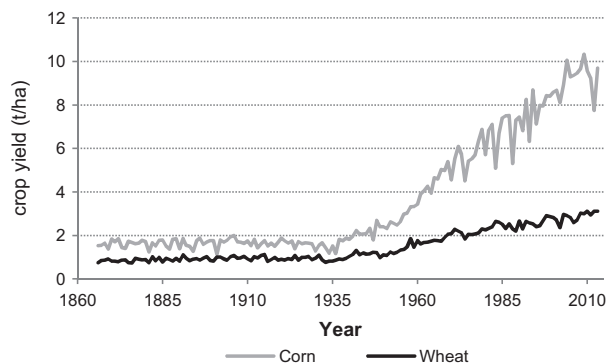




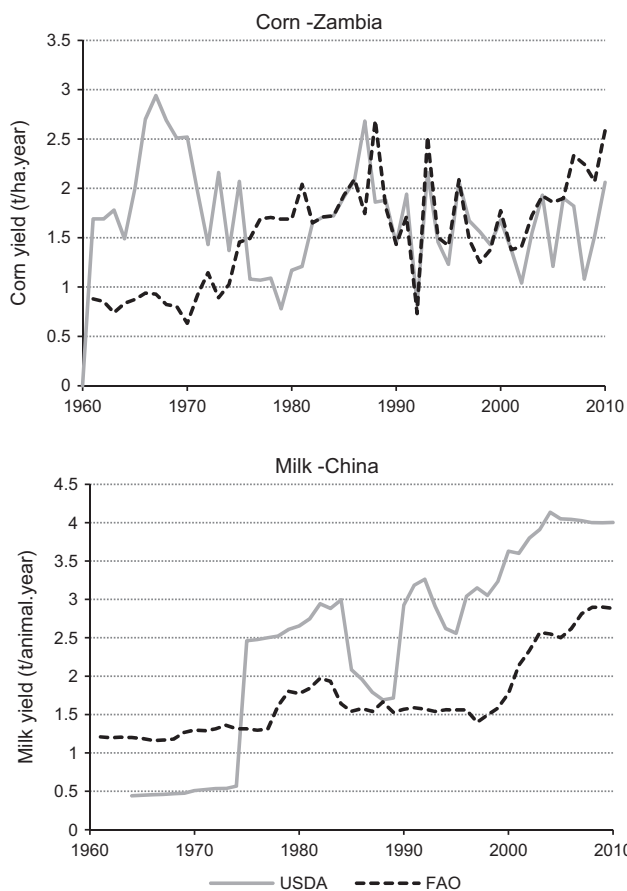
**Figure A9.** Historical yield developments (1961–2010) for the production of cattle meat and cow milk (FAOSTAT).



**Figure A10.** Development in livestock production intensity: ruminant density on pastures and meadows in livestock units per hectare ( $\text{LU ha}^{-1}$ ), derived from FAOSTAT data (FAOSTAT). Ruminants included: buffaloes, camel, cattle, goats, and sheep. Note the different scale for India compared to the other countries.



**Figure A11.** Long term historical yield trends for corn and wheat in the USA (Quick Stats).



**Figure A12.** Examples of diverging statistical yield data between FAO (FAOSTAT) and USDA (PSD Online).

**Table A1.** Comparison of average annual crop yield growth rates (% year<sup>-1</sup>) derived from (a) extrapolation of linear regression (2010–2050); (b) IMAGE projections (2010–2050); (c) MIRAGE projections (2008–2020); (d) projections from Jaggard et al. (2007–2050).

		Australia	Brazil	China	India	Zambia	Zimbabwe	USA	World
<i>Wheat</i>									
Linear extrapolation <sup>1</sup>		0.7%		1.8%	1.5%			0.8%	1.3%
IMAGE projection <sup>1,4</sup>		1.2% <sup>5</sup>		2.0%	1.4%			0.5%	1.2%
MIRAGE projection <sup>2</sup>	bau			1.4%				0.8%	1.0%
Yield projections in Jaggard et al. <sup>3</sup>	bau	1.1%		2.4%	2.0%			1.2%	
	min	0.8%		1.7%	1.4%			0.9%	
	max	1.9%		4.6%	3.9%			2.2%	
<i>Corn</i>									
Linear extrapolation <sup>1</sup>			1.6%	1.6%		1.2%	−1.6%	1.2%	1.3%
IMAGE projection <sup>1</sup>			2.4%	1.8%		1.6% <sup>7</sup>		1.2%	0.9%
MIRAGE projection <sup>2</sup>	bau		4.9%	1.8%		1.6% <sup>8</sup>		1.2%	1.5%
Yield projections in Jaggard et al. <sup>3</sup>	bau		1.7%	1.9%				1.3%	
	min		1.2%	1.3%				0.8%	
	max		3.5%	3.8%				2.7%	
<i>Rice</i>									
Linear extrapolation <sup>1</sup>		0.7%		1.3%	1.3%			1.0%	1.2%
IMAGE projection <sup>1</sup>		0.5% <sup>6</sup>		0.4%	1.8%			1.1%	1.1%
MIRAGE projection <sup>2</sup>	bau			1.6%				0.9%	2.2%
Yield projections in Jaggard et al. <sup>3</sup>	bau	0.9%		1.5%	1.4%			1.2%	
	min	0.6%		1.0%	0.9%			0.9%	
	max	1.7%		3.1%	3.0%			2.4%	
<i>Soybean</i>									
Linear extrapolation <sup>1</sup>			1.4%		1.2%	1.2%	0.6%	1.0%	1.1%
IMAGE projection <sup>1,5</sup>			1.0%		1.5%	1.7% <sup>7</sup>		1.4%	1.0%
MIRAGE projection <sup>2</sup>	bau		3.1%			2.0% <sup>8</sup>		1.1%	2.0%
Yield projections in Jaggard et al. <sup>3</sup>	bau		1.6%		1.4%			1.1%	
	min		1.1%		1.0%			0.8%	
	max		3.2%		2.9%			2.2%	
<i>Sugarcane</i>									
Linear extrapolation <sup>1</sup>		0.3%	1.0%		0.8%	−0.1%	−0.3%		0.6%
IMAGE projection <sup>1</sup>									
MIRAGE projection <sup>2</sup>	bau								
Yield projections in Jaggard et al. <sup>3</sup>	bau	0.4%	1.2%		1.1%				
	min	0.3%	0.9%		0.8%				
	max	0.7%	2.4%		2.1%				

<sup>1</sup>Relative to 2010 yields.<sup>2</sup>Relative to 2008 yields.<sup>3</sup>Relative to 2007 yields.<sup>4</sup>In IMAGE, wheat is aggregated into the product group temperate cereals.<sup>5</sup>In IMAGE, soybean is aggregated into the product group oil crops.<sup>6</sup>In IMAGE, Australia is aggregated into the region Oceania.<sup>7</sup>In IMAGE, Zambia and Zimbabwe are aggregated into the region Southern Africa.<sup>8</sup>In MIRAGE, Zambia and Zimbabwe are aggregated into the region sub-Saharan Africa.

The IMAGE model adopts yield projections from the FAO and combines these with endogenous assumptions on yield changes (Bruinsma 2003; OECD 2012). The MIRAGE model uses a baseline scenario from Aglink-Cosimo, which is also complemented by endogenous assumptions on yield developments (Laborde 2011). Jaggard et al. (2010) assume a continuation of current yield trends, but also take into account relative changes owing to increasing carbon dioxide (CO<sub>2</sub>) and ozone (O<sub>3</sub>) concentrations, climate change and technological developments.

**Table A2.** Recent yields (FAOSTAT), maximum attainable yields and yield gaps (GAEZ Global Agri-Ecological Zones) (t ha<sup>-1</sup> year<sup>-1</sup>).

		AU	BR	CN	FR	IN	ZM	ZW	US
<i>Wheat</i>									
Average yield 2008–2010	t ha <sup>-1</sup>	1.6		4.7	7.1	2.8			3.0
Max attainable yield <sup>1,3</sup>	t ha <sup>-1</sup>	3.8		6.4	8.2	3.9			6.1
Yield gap	t ha <sup>-1</sup>	2.2		1.7	1.1	1.1			3.1
Current yield as % of max	%	42		74	87	72			50
<i>Corn</i>									
Average yield 2008–2010	t ha <sup>-1</sup>		4.1	5.4	9.1		2.3	0.5	9.9
Max attainable yield <sup>1,4</sup>	t ha <sup>-1</sup>		6.6	8.4	8.8		10.9	9.8	12.6
Yield gap	t ha <sup>-1</sup>		2.5	2.9	−0.3		8.6	9.2	2.7
Current yield as % of max	%		62	65	103		21	6	78
<i>Rice</i>									
Average yield 2008–2010	t ha <sup>-1</sup>	8.9		6.6		3.3			
Max attainable yield <sup>2,5,6</sup>	t ha <sup>-1</sup>	10.7		9.5		9.2			
Yield gap	t ha <sup>-1</sup>	1.9		3.0		5.9			
Current yield as % of max	%	82		69		36			
<i>Soybean</i>									
Average yield 2008–2010	t ha <sup>-1</sup>		2.8			1.0	1.7	1.5	2.9
Max attainable yield <sup>1,7</sup>	t ha <sup>-1</sup>		3.4			3.1	4.4	4.1	3.7
Yield gap	t ha <sup>-1</sup>		0.6			2.0	2.8	2.6	0.8
Current yield as % of max	%		82			34	38	36	78
<i>Sugarcane</i>									
Average yield 2008–2010	t ha <sup>-1</sup>	80.3	79.1			66.5	105.4	79.5	
Max attainable yield <sup>2,5</sup>	t ha <sup>-1</sup>	135.3	106.8			123.1	144.1	142.1	
Yield gap	t ha <sup>-1</sup>	55.1	27.6			56.6	38.8	62.6	
Current yield as % of max	%	59	74			54	73	56	

AU, Australia; BR, Brazil; CN, China; FR, France; IN, India; ZM, Zambia; ZW, Zimbabwe; US, United States.

<sup>1</sup>Maximum attainable yield in 2020 as calculated for the IPCC SRES B1 Scenario from the Australian Commonwealth Scientific and Research Organization (CSIRO) Mark 2 Model (GAEZ Global Agri-Ecological Zones).

<sup>2</sup>Maximum attainable yield based on the average climatic conditions for the period 1961–1990, applied in case no projection for 2020 was available (GAEZ Global Agri-Ecological Zones).

<sup>3</sup>Australia, France, and the United States: high input level, rain-fed conditions; China and India: high input level, irrigated conditions.

<sup>4</sup>All countries except France and the United States: high input level, rain fed conditions; France and the United States: high input level, irrigated conditions.

<sup>5</sup>High input level, irrigated conditions.

<sup>6</sup>Maximum agrieological attainable yield for Indica wetland rice (150 days).

<sup>7</sup>High input level, rain-fed conditions.

*High input level:* “Under a high level of input (advanced management assumption), the farming system is mainly market oriented. Commercial production is a management objective. Production is based on improved or high yielding varieties, is fully mechanized with low labor intensity and uses optimum applications of nutrients and chemical pest, disease and weed control.” (GAEZ Global Agri-Ecological Zones).