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Yi-Hong Wang *Editors*

The Sorghum Genome

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The Sorghum Genome

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In memory of Dr. Neelamraju Ganaga Prasad Rao (1927–2016), father of Indian sorghum research. He had a pioneering role to bring quantum jump in the productivity of sorghum in India. The legacy he has left behind will inspire the generations to come.

Foreword

Agricultural practices need to be climate resilient so that the production system remains sustainable over a long period of time in spite of changes in climatic conditions. Millets in general, with their inherent drought tolerance and ability to yield substantially under the most neglected crop management, are climate resilient. Besides, they are a good source of micronutrients and have low glycemic indices. Thus, they fit best in the current food and agricultural scenario.

Sorghum or the 'big millet' represents nearly 60% of area being covered by millets across the world, mainly being cultivated by the resource-poor farmers of semi-arid tropics of Asia and Africa. In addition to meeting the calorific requirement of the human population particularly in rainfed regions, sorghum commands an important place as a source of feed and fodder for large animal populations in this region. In recent past, sorghum assumed renewed importance as an alternate source of biofuel. With its C4 photosynthetic pathway, sorghum has become a model plant system to understand the genetic architecture of grass family through comparative 'omics' studies.

With publication of its genome sequence sorghum has turned out to be the most sought-after system to understand the genomic architecture of C4 plants. Since 2009, a good number of studies on re-sequencing of sorghum genotypes have brought out a fair understanding of the genome organization and sequence diversity, which are being deployed in association mapping. The available information on genomic variation has its potential use in genomic selection of sorghum and allied crops. However, all these achievements have been possible through initial studies on cytogenetics, germplasm characterization, construction of genetic and physical maps, and identification of QTLs for traits of interest.

I appreciate the efforts of the editors to organize 15 chapters in this book in such a way that all these developments have been brought out in the right perspective by eminent groups of scientists across the world. I am sure that this book will be of utility to the students, scientists working on sorghum and other field crops, science managers and policy makers.

New Delhi, India
September, 2016

T. Mohapatra

Preface

The biggest challenge facing agricultural scientists is to feed an ever-increasing human population, which is expected to reach 9.1 billion by 2050. The demand for cereals, for both food and animal feed uses, is projected to reach around 3 billion tons by 2050 from 2.1 billion tons today. This gap is to be filled in spite of decreasing availability of arable land, deteriorating soil fertility, and increased incidences of climatic extremes. Under that context, agriculturists need to make the agricultural practices more climate resilient. Sorghum is the fifth most important cereal crop after rice, wheat, maize, and barley, and is extensively grown in the semi-arid tropics of the world thanks to its inherent ability to tolerate harsh environments. Thus, this is a model crop among grass species to study stress response and ensuring food security for millions of poor masses living in the most impoverished drought-prone regions of the world. Sorghum not only provides food and feed but also serves as an important source of fodder for large cattle with its dry stover. Green plants are also a source of forage for cattle. In recent years, sweet sorghum has turned out to be a source of ethanol production and second-generation lignocellulose-based biofuels. Thus, sorghum has the potential to provide food, feed, fodder, and fuel.

Unlike other cereals such as rice, wheat, and maize, sorghum received lesser attention with regard to genetic and genomics studies in the past. The lesser economic importance of sorghum is the principal reason behind this. However, over the last two and a half decades much progress has been made in this area. After publication of the rice genome sequence, sorghum turned out to be a natural complement to rice in understanding the complexity of the genomes of this most important group of crop plants, that is, the grass family. With its proximity not only to cereal crops but also to commercial crops including sugarcane, sorghum has turned out to be a model crop to initiate genomics research through syntenic studies. With publication of the sorghum genome sequence in 2009, the scenario was revolutionized and this neglected crop started receiving prominence in genomics studies. Stress tolerance of the crop proved to be an added advantage for its popularity.

Over the period of a few decades many reports on sorghum genomics as well as transgenic research have come into the public domain, which deals with almost all traits related to the crop. These studies have exhibited promise to improve the crop further in terms of stress tolerance and yielding ability.

This has also opened up opportunity to improve other related crops as well, using the genomics information generated in sorghum.

The current volume, Compendium of Plant Genomes: The Sorghum Genome, comprises 15 chapters. Chapter 1 deals with the global status of the crop and its economic importance. It has been observed that sorghum yield levels have increased in almost all the sorghum-growing regions except Africa, and this has been achieved both due to genetic gains in the released cultivars and better crop management. Consumption of sorghum as food is declining because of changes in food habits and consumer preference. However, use for animal feed and other industrial purposes is increasing. The world sorghum trade is mainly linked to demand for livestock products. Chapter 2 is devoted to the botany, floral biology, and classification of sorghum and their implications for the breeding methods to be used. It highlights how understanding of botany and taxonomy could be effectively used for improving sorghum yield and nutritional quality.

Genomic studies of a crop are partially dependent on availability of cytogenetic information on it. Due to inherent small sizes of sorghum chromosomes such studies are scanty. Chapter 3 details the progress in molecular cytogenetics that has paved the way for genome sequencing of the crop and for understanding its genetic architecture. Furthermore, sorghum germplasm is best characterized among crop plants, which have been grouped into core and mini-core collections and a genotyping-based reference set. These have been characterized systematically to identify sources of resistance against various stresses and quality traits. All these developments are narrated in Chap. 4.

Completion of sorghum genome sequencing after that of Arabidopsis and rice is a big step leading to widespread genomics applications. Chapter 5 elaborates international private and public efforts leading to sorghum genome sequencing. The chapter also discusses a postgenomic scenario in the context of next-generation sequencing and beyond. Progress in sorghum genomics leading to elaborate syntenic studies with allied and model genomes as well as the computation needs and implications have been described in Chap. 6. Progress in crop genomics has forged a new path of gene mapping in the form of association mapping, paving the way for genomic selection. As compared to fine cereals and maize, progress in this regard in sorghum is meager. The current status is dealt with in Chap. 7.

Although sorghum is relatively stress tolerant, like other crop plants its productivity is affected by various stresses, including biotic and abiotic stresses. Chapter 8 explores the application of genomic approaches such as large-scale genotyping and high-throughput sequencing towards genetic linkage mapping, association studies, and marker-assisted selection for biotic stresses. Chapter 9 describes similar progress for abiotic stresses, for which less success have been recorded. Chapter 10 provides the current status of the application of genomics tools in improving sorghum grain quality, be it starch quality or composition of seed proteins and nonstarch polysaccharides. Underground root architecture plays a vital role in moisture and nutrient acquisition by the plants from the soil, which most commonly remains unexplored. Chapter 11 focuses on sorghum root architecture, its screening tools, and the status of QTL analysis.

Overexpression and gene knockout studies play a vital role in gene discovery and their characterization; both are dependent on efficient transformation protocols. Chapter 12 examines studies that improve transformation efficiency in sorghum and enhance biotic and abiotic stress tolerance and nutritional quality using transgenic approaches. Chapter 13 reviews positional or map-based cloning of economically important genes/alleles and their characterization leading to their effective deployment in improvement of sorghum. The chapter further describes cloning strategies used to identify the underlying mutations of economic significance. TILLING, a reverse genomics tool, and its variant eco-TILLING, are novel tools for the discovery of genes and/or their mutant forms. Chapter 14 provides an account of this new dimension in TILLING/Eco-TILLING and its implication in sorghum genomics. Plant–microbiome interaction is a very dynamic phenomenon, being influenced by environmental stimuli. Such studies are limited in sorghum, which are elaborated in Chap. 15. Genomics and transcriptomics studies, which can be designed to understand the microbial communities associated with sorghum, are also described in this chapter.

The chapters of this book have been authored by a team of scientists who are expert in their respective fields of research in sorghum involving both conventional and genomics tools. Sincere efforts have been made to avoid overlapping in contents, however, some overlapping in isolated spots is unavoidable.

Some books in this area have already been published in the recent past by an international group of scientists. We have made efforts to include updated information in the chapters, and we believe that this book will be of much use to the sorghum research community. Any omission in the book is our responsibility and will be addressed in future editions.

We express our sincere thanks to the 42 contributors for their chapters. We sincerely appreciate their continuous cooperation starting from first submission of drafts to revision of their chapters matching with the reviews. We also thank our family members for bearing with us throughout the process of editing and finalization of this book.

Finally, we put on record our most sincere thanks to the series editor, Prof. C. R. Kole for giving us this opportunity to edit this book and Springer-Verlag and its entire staff, particularly Dr. Jutta Lindenborn and Ms. Abirami Purushothaman, for their kind understanding and help in publication and promotion of this book. We hope that this book will be useful to students, scientists both in academia and industry, and policy makers.

Hyderabad, India Sujay Rakshit
Lafayette, USA Yi-Hong Wang

Contents

Economic Importance of Sorghum

1

K. Hariprasanna and Sujay Rakshit

Abstract

Sorghum acts as a dietary staple for millions of people living in about 30 countries in the subtropical and semi-arid regions of Africa and Asia. It is a source of food and fodder, mostly in the traditional, smallholder farming sector. It also finds a place in the high-input commercial farming sector as a feed crop, and is fast emerging as a biofuel crop. More than 80 % of the global sorghum area is characterized by low yield levels contributing to slightly above half of total grain output whereas the rest comes from the developed world with high yield levels. Though sorghum cultivation is reported from more than 100 countries, only eight countries have over 1 million ha area under sorghum, which together contribute more than 60 % of world sorghum production. In Africa, although only a few countries contribute a major share of area, sorghum is widely distributed and is a major staple food grain in large parts of the continent. In spite of its economic importance, sorghum cropped area around the world has declined over the last four decades at a rate of over 0.15 million ha per year. However, in some countries including Brazil, Ethiopia, Sudan, Australia, Mexico, Nigeria, and Burkina Faso it is expanding, mainly because of new land brought under sorghum cultivation or diversion of a portion of area planted to other crops such as maize and wheat. Global sorghum production peaked during the mid-1980s, and thereafter it declined by about 13–15 %, but not steadily. In almost all the sorghum growing regions except Africa yield levels have been enhanced over the years as a result of improved cultivars, higher input use, better resources, and crop management. Most of the sorghum is consumed in the countries where it is produced and world trade is mainly linked to demand for livestock products, which is governed by the feed requirements and prices in developed countries. Consumption of sorghum for food purposes is declining because of a change in food habits and consumer preference

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brought about by economic status, whereas use for animal feed and other industrial purposes is increasing. Under a changing climate regime sorghum would assume renewed importance as a food and industrial crop, and therefore concerted focus is necessary on such marginalized crops to ensure food and nutritional security in a sustainable manner in the years to come.

1 Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal in terms of production and area harvested in the world. It is one of the most important dryland food crops grown in marginal lands in more than 100 countries, and is a dietary staple of more than 500 million poor and the most food-insecure people living in about 30 countries in the subtropical and semi-arid regions of Africa and Asia (Kumar et al. 2011). The *Sorghum* genus has many species and subspecies. There are several types of sorghum, including grain sorghums, forage sorghums (for pasture and hay), sweet sorghums (for syrups and biofuel), and Broomcorn. The crop is agronomically suited to hot and dry agroecologies where other food grains fail to yield substantially or are even difficult to grow. In these agroecologies sorghum is a dual-purpose crop, as both grain and stalks or stover are highly valued for human and animal consumption, respectively. In developed countries such as the United States, Japan, and Australia, and in some developing countries including China and Mexico, grains are important as animal and bird feed. In large parts of the developing world, stover represents up to 50 % of the total value of the crop, particularly in drought years (ICRISAT & FAO 1996).

The sorghum-based world economy has two distinct segments: a traditional, smallholder farming sector (largely in Asia and Africa as subsistence farming), and a modern high-input large-scale farming sector (principally in the developed countries and in Latin America; ICRISAT & FAO 1996). More than 80 % of the global sorghum area of 42.12 m ha (FAO 2015) lies in developing countries on the African and Asian continents (Fig. 1), where sorghum is grown primarily for food by low-income farmers. The remaining area of 16–20 % is predominantly in the developed world, especially cultivated by large-scale commercial farms, which produce sorghum mainly for animal feed. The yield levels are high in the latter sector because of the use of modern agricultural practices. Africa and Asia together account for approximately 56 % of global sorghum production, whereas the Americas contribute nearly 38 % of global output from just about 16 % of the global harvested area (Fig. 2). Production in Africa is characterized by low productivity and extensive, low-input cultivation, whereas production is generally more intensive in Asia, where improved cultivars and fertilizers are used more widely (ICRISAT & FAO 1996). Though developed countries in general are feed producers, some developing countries such as Mexico and Argentina are also major producers of sorghum for the feed market.

2 Origin and Distribution

The origin and early domestication of sorghum is hypothesized to have taken place in northeastern Africa or at the Egyptian–Sudanese border around 5000–8000 years ago (Mann et al. 1983). The largest diversity of cultivated and wild sorghum is observed in this part of Africa. From the site of early domestication, sorghum later spread to other parts of Africa and eventually to Asia including India, the Middle East, and China (Doggett 1970). Among the five different cultivated races, *durra* types presently extend from Ethiopia along the river Nile to the Near East, and farther to Thailand and across India. The *durra* types were probably introduced to Arabia as early as the Sabian Empire (1000–800 BC),

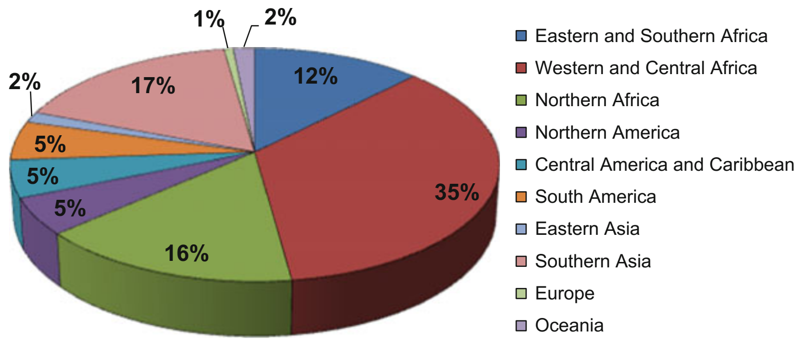

Fig. 1 World sorghum area (3-year average for 2011–2013)

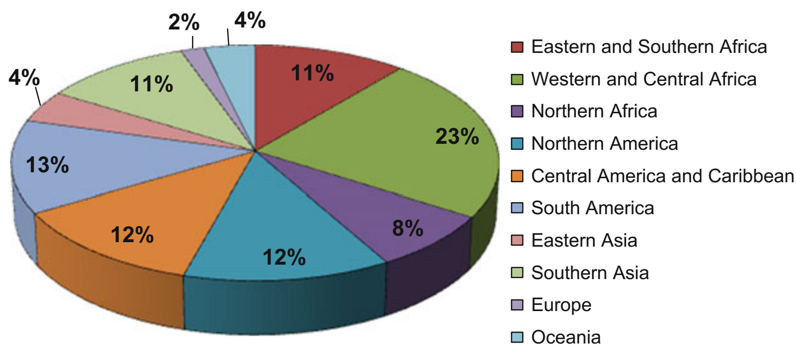

Fig. 2 World sorghum production (3-year average for 2011–2013)

and later spread to the Near East along trade routes (House 1985). Sorghum probably reached India by both land and sea routes. The secondary center of the origin of sorghum is the Indian subcontinent, with evidence for early cereal cultivation discovered at an archaeological site in western parts of Rojdi (Saurashtra) dating back about 4500 years (Vavilov 1992; Damania 2002).

The first written record of sorghum is from the first century AD, found in writings by the Roman, Pliny (Martin 1970; Smith and Frederiksen 2000). Possibly sorghum was introduced to the Near East at about the same time it appeared in Italy. Pliny recorded (in approximately 60–70 AD) that the crop was introduced to Italy from India. Distribution suggests that sorghum was probably introduced to China from India about the third century AD. The presence of *durra* types in Korea and adjacent Chinese provinces suggests that it may have been introduced there via the ancient Silk Routes from Asia Minor (House 1985). Sorghum is relatively new to the American continent. It is supposed that grain sorghum was first introduced to North America through the West Indies by African slaves during the seventeenth century. Even after widespread distribution in the Americas, production slowly dropped off until it almost disappeared (Maunder 1999). The reintroduction of grain sorghum into America occurred in California in 1874, and shortly after that it became widespread in the southern Great Plains and other arid regions of the United States as it was recognized as a drought-tolerant crop that would outperform maize (Smith and Frederiksen 2000). It was extensively used in the early 1900s for syrup (Doggett 1965). Its cultivation in Central and South America has become significant only since 1950 (House 1985).

3 Cropping Area

Sorghum is cultivated in 105 countries (Rakshit et al. 2014). Among these, 37 countries have more than 0.1 m ha sorghum harvested area and eight countries (Sudan, India, Nigeria, Niger, United States, Ethiopia, Burkina Faso, and Mexico in decreasing order) have over 1 m ha area under sorghum, which together contribute 71 % of world sorghum harvested area. In western and central Africa, sorghum is grown between the Sahara desert in the north and the equatorial forests in the south. In southern and eastern Africa it is grown predominantly in drier regions (FAO & ICRISAT 1996). Sudan has the largest area under sorghum in northern Africa and the area has increased more than four times during 2011–2013 compared to 1961–1963 (Table 1). In Asia, geographically only India and China are important sorghum-growing countries. In the Americas, the United States has the largest area followed by Mexico. In South America, Argentina and Brazil have some appreciable acreage under sorghum. Australia grows sorghum on more than 0.6 m ha. A few countries in Africa contribute the major share of area, sorghum is widely distributed, and is a major staple food grain in large parts of the continent.

In spite of the importance of the crop, over the last four decades the sorghum cropped area around the world has reduced at a rate of over 154,000 ha per year (Rakshit et al. 2014). In those countries with the maximum area, such as China, the United States, and India, the cropped area has dropped drastically. In the case of China the sorghum-growing area has declined more than 11-fold compared to 1961–1963 levels, whereas in India the area decline is almost to the tune of 60–65 % of the area sown to sorghum during the early 1960s. In the United States, the area has come down by more than 55 % in 2011–2013 compared to 1961–1963 levels. Another western Asian country with appreciable area under sorghum is Yemen, which also recorded area reduction of over 50 % of the 1961 levels. On the other hand, in some countries area has tremendously increased over the years. Brazil recorded maximum proportional increase in area compared to the 1970 level followed by Ethiopia, Sudan, Australia, Mexico, Nigeria, and Burkina Faso. In Brazil, sorghum area has increased significantly since 1995, whereas in Mexico the area has increased since the 1970s by more than 60 % compared to 1971–1973 but recorded a slow increase from 1981 onwards. The loss in area in Asia is attributed to the change in food habits, low profitability of the crop, and lack of government support, whereas that in the United States is due to government policy allowing marginal lands to be placed under the Conservation Reserve Program and competition from genetically modified maize hybrids. On the other hand, an increase in area in countries such as Australia is because of new land being brought under cultivation, higher cropping intensity with better water management, and in the recent past due to allocation of land under wheat and barley to sorghum. The steady increase in sorghum area, particularly since the 1990s in African countries is attributed to new land being brought under cultivation and some from former maize acreage. In South American countries some portion of the area planted with maize, wheat, and other crops was gradually brought under sorghum leading to an increase in sorghum area (Rakshit et al. 2014).

4 Production

Developed countries produce more than one-third of the world's sorghum and the remainder comes from the rest of the world where more than 70 % of the sorghum area is geographically located. With over 16 % of global output the United States is the world's largest producer. In the United States, sorghum cultivation is concentrated in the central and southern Great Plains where rainfall is low and variable. Nearly 90 % of the grain sorghum in the United States is produced in five states: Kansas, Oklahoma, Texas, Nebraska, and Missouri. Sorghum production in Central America and the Caribbean is dominated by Mexico, which accounts for 94 % of the region's total production. In South America production is concentrated in Argentina (56 % of the region's total) and in the dry areas

Table 1 Sorghum area and production by region/country[a]

	Area (lakh ha)						Production (lakh tonnes)					
	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013
Africa	**134.76**	**141.00**	**137.29**	**209.65**	**238.45**	**255.25**	**109.46**	**104.81**	**124.66**	**164.23**	**211.75**	**239.77**
Northern Africa	**17.86**	**22.62**	**39.37**	**55.08**	**61.21**	**63.22**	**21.24**	**24.61**	**30.59**	**40.97**	**50.56**	**44.61**
Egypt	1.95	2.05	1.66	1.44	1.57	1.47	6.90	8.46	6.23	7.40	9.08	7.82
Morocco	1.32	0.67	0.35	0.31	0.18	0.07	0.80	0.77	0.22	0.18	0.11	0.06
Sudan (former)	14.44	19.74	37.20	53.28	59.42	61.65	13.49	15.28	24.08	33.36	41.36	36.71
Western Africa	**74.62**	**74.05**	**56.39**	**110.30**	**126.61**	**121.83**	**56.81**	**44.48**	**55.22**	**89.20**	**112.87**	**110.44**
Benin	1.13	0.90	0.98	1.43	1.83	1.10	0.60	0.59	0.58	1.10	1.75	1.19
Burkina Faso	9.52	10.38	10.73	12.98	15.46	17.57	4.60	4.89	6.26	12.70	14.52	17.90
Cote d'Ivoire	0.14	0.31	0.34	0.48	0.58	0.68	0.10	0.15	0.18	0.27	0.34	0.48
Gambia	0.07	0.07	0.07	0.11	0.24	0.31	0.07	0.07	0.07	0.11	0.26	0.23
Ghana	1.56	2.18	2.11	2.93	3.37	2.34	1.05	1.64	1.21	2.76	3.11	2.75
Guinea	0.20	0.20	0.20	0.18	0.35	0.36	0.24	0.25	0.24	0.27	0.34	0.48
Guinea-Bissau	0.04	0.06	0.35	0.14	0.16	0.24	0.03	0.03	0.23	0.13	0.13	0.23
Mali	5.15	3.73	5.34	8.91	8.16	11.61	3.49	2.84	4.52	7.16	6.29	10.74
Mauritania	2.10	1.71	1.11	1.28	1.36	1.27	0.82	0.35	0.31	0.67	0.53	0.50
Niger	4.67	5.31	10.75	23.14	23.72	30.30	3.16	2.00	3.45	3.80	6.83	11.57
Nigeria	48.88	47.92	22.16	55.39	67.40	52.97	41.72	30.72	35.99	57.76	75.44	68.32
Senegal	1.09	1.22	1.13	1.19	1.94	1.41	0.81	0.87	1.23	0.98	1.52	1.05
Sierra Leone	0.07	0.05	0.09	0.37	0.16	0.30	0.12	0.06	0.13	0.23	0.18	0.34
Togo			1.03	1.77	1.85	2.18			0.81	1.27	1.63	2.50
Central Africa	**10.54**	**9.06**	**7.69**	**10.43**	**12.83**	**20.18**	**7.34**	**5.67**	**5.08**	**7.20**	**11.20**	**20.82**
Angola					0.53	1.65					0.17	0.40
Cameroon	3.01	3.43	4.04	5.10	4.11	7.78	2.55	2.43	2.66	3.90	5.40	11.33
Central African Rep.	0.62	0.47	0.54	0.17	0.47	0.40	0.33	0.38	0.43	0.20	0.42	0.47

(continued)

Table 1 (continued)

	Area (lakh ha)						Production (lakh tonnes)					
	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013
Chad	6.53	4.86	2.73	5.07	7.62	8.60	4.20	2.59	1.66	3.05	5.14	8.55
DR of the Congo	0.39	0.30	0.38	0.09	0.10	0.09	0.26	0.27	0.34	0.05	0.06	0.07
Eastern Africa	**26.26**	**30.31**	**30.09**	**30.52**	**36.14**	**48.44**	**20.48**	**24.76**	**29.64**	**23.11**	**34.20**	**62.00**
Burundi	0.20	0.21	0.53	0.58	0.57	0.57	0.20	0.20	0.53	0.66	0.71	0.50
Eritrea				14.03	1.83	2.56	0.00	0.00	0.00	0.45	0.57	0.78
Ethiopia	10.23	9.87	9.06	4.48	12.76	18.27	8.11	9.32	13.25	6.28	16.26	39.65
Kenya	1.61	2.04	0.97	1.17	1.43	2.29	1.77	2.27	0.61	1.09	1.20	1.55
Malawi	0.71	1.20	0.28	0.34	0.56	0.86	0.45	0.96	0.16	0.15	0.40	0.75
Mozambique	2.17	2.50	3.33	4.08	2.95	6.28	1.71	2.09	1.97	1.23	1.68	2.79
Rwanda	1.04	1.30	1.78	1.37	1.79	1.09	1.32	1.42	1.98	1.49	1.77	1.49
Somalia	3.83	3.80	4.64	3.10	3.58	2.43	1.32	1.33	1.92	1.06	1.33	1.71
Uganda	2.94	3.04	1.92	2.50	2.86	3.62	2.78	3.85	3.32	3.74	4.24	3.57
UR of Tanzania	1.79	3.38	5.00	6.42	5.99	7.87	1.78	1.73	4.93	6.39	5.09	8.26
Zambia	0.68	0.74	0.20	0.40	0.27	0.20	0.41	0.47	0.13	0.23	0.18	0.16
Zimbabwe	1.02	2.20	2.35	1.12	1.53	2.43	0.61	1.12	0.81	0.62	0.75	0.76
Southern Africa	**5.48**	**4.97**	**3.76**	**3.31**	**1.67**	**1.58**	**3.59**	**5.28**	**4.13**	**3.75**	**2.92**	**1.91**
Botswana	0.87	0.97	0.65	0.72	0.23	0.65	0.28	0.51	0.12	0.29	0.21	0.35
Lesotho	0.65	0.70	0.52	0.30	0.35	0.16	0.55	0.42	0.35	0.27	0.23	0.06
Namibia	0.12	0.22	0.31	0.29	0.21	0.17	0.02	0.05	0.07	0.07	0.07	0.07
South Africa	3.64	3.05	2.27	1.99	0.86	0.59	2.63	4.28	3.59	3.12	2.41	1.47
Asia	**267.39**	**230.92**	**205.34**	**152.14**	**114.49**	**82.61**	**167.08**	**178.47**	**200.07**	**169.65**	**113.17**	**99.49**
Eastern Asia	**67.17**	**51.03**	**27.19**	**13.79**	**8.01**	**5.97**	**65.12**	**87.12**	**73.65**	**51.64**	**30.04**	**25.40**
China	66.70	50.67	27.00	13.43	7.83	5.32	64.67	86.67	73.30	50.41	29.62	20.22
DP Rep. of Korea	0.31	0.23	0.12	0.09	0.13	0.21	0.34	0.27	0.18	0.11	0.21	0.37

(continued)

Table 1 (continued)

	Area (lakh ha)						Production (lakh tonnes)					
	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013
Southern Asia	**188.37**	**168.69**	**168.62**	**130.88**	**98.29**	**68.07**	**92.40**	**82.61**	**118.02**	**109.99**	**74.35**	**62.14**
India	183.46	163.35	164.69	127.04	94.65	66.04	89.92	79.29	115.78	107.73	72.13	60.88
Pakistan	4.89	5.32	3.91	3.84	3.63	2.03	2.46	3.31	2.23	2.25	2.21	1.28
Southeastern Asia	**0.08**	**0.76**	**2.57**	**1.71**	**3.00**	**2.54**	**0.20**	**1.42**	**2.90**	**2.36**	**2.88**	**2.72**
Thailand	0.08	0.70	2.51	1.71	0.69	0.29	0.20	1.29	2.79	2.36	1.24	0.55
Myanmar					2.31	2.25					1.64	2.16
Western Asia	**11.76**	**10.44**	**6.96**	**5.68**	**5.13**	**6.01**	**9.37**	**7.33**	**5.50**	**5.53**	**5.78**	**9.16**
Iraq	0.06	0.07	0.06	0.02	0.04	0.22	0.04	0.07	0.06	0.01	0.03	0.70
Israel	0.16	0.09	0.04	0	0.04	0.06	0.39	0.30	0.17	0	0.20	0.32
Saudi Arabia	1.10	1.60	1.10	1.32	1.62	0.70	1.62	0.68	0.66	1.47	2.43	2.16
Yemen	10.35	8.66	5.75	4.24	3.35	4.88	7.25	6.26	4.60	3.93	2.95	4.37
Americas	**62.65**	**99.33**	**101.12**	**72.73**	**69.88**	**63.14**	**155.27**	**298.74**	**336.19**	**259.11**	**224.92**	**215.51**
Northern America (United States)	**48.40**	**60.77**	**51.01**	**41.60**	**31.70**	**20.79**	**133.43**	**219.51**	**186.14**	**168.84**	**108.89**	**72.00**
Central America	**3.68**	**13.39**	**17.86**	**15.48**	**21.32**	**19.56**	**5.40**	**30.98**	**56.27**	**45.46**	**64.61**	**69.06**
El Salvador	0.96	1.25	1.15	1.35	0.87	0.95	0.88	1.53	1.28	1.94	1.44	1.40
Guatemala	0.31	0.41	0.40	0.68	0.43	0.27	0.19	0.41	0.82	0.80	0.52	0.44
Honduras	0.42	0.43	0.56	0.73	0.58	0.33	0.50	0.46	0.54	0.76	0.66	0.41
Mexico	1.44	10.76	14.99	12.11	18.86	17.46	3.30	27.99	52.24	40.81	60.78	65.69
Nicaragua	0.50	0.45	0.47	0.51	0.52	0.44	0.47	0.45	0.92	0.88	1.08	0.79
Caribbean	**2.24**	**2.04**	**1.67**	**1.28**	**1.23**	**1.27**	**2.13**	**2.05**	**1.42**	**1.10**	**0.94**	**1.15**
Haiti	2.00	1.98	1.57	1.20	1.19	1.23	1.84	1.87	1.14	0.92	0.87	1.09
South America	**8.33**	**23.13**	**30.58**	**14.37**	**15.63**	**21.52**	**14.30**	**46.20**	**92.35**	**43.72**	**50.48**	**73.30**
Argentina	8.25	20.74	23.77	7.21	5.62	9.39	14.17	41.40	78.83	26.26	28.14	41.16

(continued)

Table 1 (continued)

	Area (lakh ha)						Production (lakh tonnes)					
	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013
Bolivia			0.04	0.22	0.53	1.42	0.00	0.00	0.13	0.70	1.36	3.75
Brazil	0.00	0.50	1.17	1.59	5.55	7.39	0.00	0.85	2.24	2.74	11.69	20.07
Colombia	0.04	1.04	2.65	2.34	0.71	0.13	0.08	2.43	5.65	7.08	2.36	0.52
Ecuador				0.02	0.06	0.09			0.01	0.03	0.10	0.14
Paraguay	0.03	0.05	0.08	0.14	0.29	0.25	0.03	0.06	0.10	0.19	0.37	1.26
Uruguay		0.70	0.62	0.40	0.23	0.56		1.18	1.43	1.21	0.88	2.35
Venezuela		0.05	2.15	2.39	2.64	2.22		0.06	3.63	5.33	5.59	3.87
Europe	**1.52**	**2.11**	**2.86**	**2.18**	**1.71**	**2.77**	**1.73**	**5.62**	**7.07**	**8.50**	**6.67**	**9.87**
France	0.13	0.68	0.59	0.85	0.67	0.46	0.36	2.58	2.76	4.89	3.63	2.67
Italy	0.05	0.03	0.21	0.32	0.33	0.42	0.18	0.09	1.05	1.85	1.96	2.50
Romania	0.06	0.02	0.16	0.06	0.04	0.18	0.08	0.03	0.20	0.05	0.04	0.42
Russian Federation (USSR)	0.77	0.57	1.25	1.10	0.32	0.77	0.62	0.68	1.30	1.21	0.32	0.92
Spain	0.01	0.43	0.27	0.11	0.08	0.08	0.01	1.72	1.12	0.58	0.28	0.43
Ukraine				0.11	0.15	0.66				0.09	0.17	2.23
Oceania	**1.36**	**6.30**	**6.73**	**4.59**	**7.51**	**6.30**	**2.33**	**11.83**	**11.62**	**9.17**	**18.11**	**21.39**
Australia	1.36	6.29	6.71	4.58	7.49	6.29	2.32	11.81	11.60	9.15	18.07	21.34
World	**467.68**	**479.66**	**453.33**	**441.29**	**432.03**	**410.07**	**435.86**	**599.47**	**679.61**	**610.65**	**574.61**	**586.04**

[a]Each figure is a 3-year average for the respective period, for example, 1961–1963

of Brazil (27 % of the region's total). Production in Europe is limited to small areas in France, Italy, and Ukraine. In Oceania, Australia is the only significant producer. Production in Asia is far more concentrated in just two countries, China and India, which together contribute more than 85 % of the regional total (Table 1). In India, the main sorghum-producing states are Maharashtra, Karnataka, Telangana, Madhya Pradesh, and Gujarat. In the recent past, sorghum has been gaining increased popularity in coastal Andhra Pradesh under a rice-fallow situation (Chapke et al. 2011). Sorghum production in China is concentrated in the drier regions of the north and especially the northeast. However, it is distributed from Taiwan in the east, Xinjiang in the west, to Aihui county in Heilongjiang in the northeast, and to Sisha Island in the south (Gao et al. 2010). In northern Africa, Sudan is the largest sorghum producer, and production levels have nearly tripled compared to production during 1961–1963. Nigeria is the major sorghum producer in western Africa and production has increased there by more than 60 % in the period 2011–2013 over 1961–1963. However, a lot of variation has been observed over the years both in area harvested and production. In central Africa, Cameroon is the largest producer whereas in eastern Africa, Ethiopia is the biggest sorghum producer with all other countries far behind with respect to quantity of grain produced.

Global sorghum production peaked during 1985 with 77.57 m tons of grain, nearly 90 % more than the production levels recorded in the early 1960s. During the period of 1981–1983 to 2011–2013 global sorghum production fell by 13–15 % with a mean of 0.75 % per annum and the area declined during the corresponding period by 9.9 %. The decline in sorghum production is in contrast to annual increases in the production of other major grains such as rice, wheat, and maize. During the 50-year period from 1961, production grew mostly in Africa especially in Sudan, Burkina Faso, Ghana, Mali, Niger and Nigeria (North and Western Africa), Cameroon, Chad, and Ethiopia (Central and Eastern Africa), but declined in most other parts of the world, particularly in North America and Asia. Mexico in Central America and Brazil in South America exhibited significant growth in sorghum production during the period. Argentina had a significant increase in production till 1983, commensurate with the increase in area under sorghum followed by a decline in area but a gradual increase in production, indicating an increase in productivity. The sorghum production in Argentina fell from 8 m tons in 1983 to 2 m tons in 1990, as a result of a drastic fall in imports by the former USSR (ICRISAT & FAO 1996).

In Asia, production has fallen over the past three decades largely because of sharp declines in area, particularly in China and India. The drop in per capita consumption of sorghum as food occurred mainly because an increase in income levels, urbanization, changing food habits and preferences has led to a decline in cultivated area. In India, production grew by almost 5 % per annum during the 1970s, remained unchanged during the next two decades, and then started declining as sorghum has been replaced by more profitable crops such as soybean, cotton, and maize. The loss in area was partly compensated by higher productivity obtained through use of improved varieties and better management. In Africa, in contrast, production increase was due to area expansion into drier lands as a result of population growth although yield levels did not increase. Among developing countries, in Argentina and Mexico, production fell by nearly 40 % during the late 1980s, essentially because of policy interventions that led to a reduction in sorghum area.

5 Productivity

Enhanced yield levels have been observed in almost all the sorghum-growing countries as a result of improved cultivars, higher input use, and better resource and crop management. The exception is Africa, where yields declined by 14 % during the 1980s before increasing in the early 1990s. In India, productivity varies widely between regions depending on rainfall, soil type, and season. India has two adaptive types, rainy season sorghum and post-rainy season sorghum (Rakshit et al. 2012; Patil et al. 2013). Yields in rainy season sorghum range between 2.5 and 3.5 t/ha in areas with deep soils and assured moisture, but post-rainy season yields are less than 1 t/ha as the crop is raised predominantly under receding soil moisture in low-depth soils. There are sharp differences in productivity between regions/countries essentially due to the degree of commercialization and the corresponding adoption of new technologies. For example, yield levels (2011–13 average) were more than 1.2 t/ha in Eastern and Southern Africa, less than 0.7 t/ha in Northern Africa, and less than 1 t/ha in Southern Asia (Fig. 3a), whereas they were more than 3.4 t/ha in the Americas, more than 3.7 t/ha in Europe, and more than 4 t/ha in Eastern Asia (Fig. 3b). Dramatic growth in Mexico has been recorded where average yields rose to over 3.7 t/ha by 2013 from about 2.5 t/ha in the early 1960s. In a number of developed countries, the use of hybrid seed, fertilizer, and irrigation have ensured that yield levels have increased even from a high base level (ICRISAT & FAO 11996). In contrast, in many of the developing countries most of the sorghum is produced on small and fragmented plots, poor soils, and where there is generally limited use of purchased inputs due to the economic status of the growers. In Sudan the yield levels have dropped over the years (Rakshit et al. 2014), and this is principally due to the expansion of cultivated area to more marginal lands leading to a decline in overall productivity of Northern Africa (Fig. 3a). However, Sudan and some other developing countries including Zimbabwe also produce sorghum on large farms for commercial purposes using high inputs and irrigation. Under such conditions, yield levels up to 3 t/ha have been recorded by commercial farmers compared to the national average of 500 to 670 kg/ha.

Hybrids are most widely adopted in areas where sorghum is commercially produced and in countries with a well-developed private seed industry and complementary legislation. In most of the developing countries except China, India, Thailand, Sudan, and Zimbabwe, the use of hybrids is negligible. Most hybrids are developed for feed sorghum. However, hybrids are also being developed for food grain purposes in some of the developing countries, especially in India where hybrids occupy more than 85 % of sorghum area during the rainy season (Reddy et al. 2006). In many African countries, population growth forced expansion of the sorghum area into drier and more hostile lands, resulting in a reduction in productivity. However, in some other countries government policies have also led to the reduction in sorghum productivity as a result of relocation of productive sorghum fields to maize or other crops and pushing sorghum to more marginal lands.

Among the top sorghum producers, which produce more than 1 m tons (2011–2013) of grains annually, the highest yield levels are recorded in Argentina followed by China, Mexico, the United States, and Australia (Table 2). In Argentina, the yield levels rose by 155 % during 1961–1963 and 2011–2013, and in China the yield rose threefold during the same period. The relative rise in productivity levels is lower in the United States (25 %) and Mexico (60 %), but in Australia productivity almost doubled in the 50 years between 1961–1963 and 2011–2013. Among the other top producers, the jump in yield levels ranged from 9 % (Brazil) to 174 % (Ethiopia), whereas in Sudan the yield levels have gone down by 38 %, a clear-cut indication of the spread of sorghum to less-productive soils and poor management.

Analysis of yield gain over the years in the top 10 sorghum-producing countries from 1970 to 2009 by Rakshit and others (2014) indicated that relative to yield level of 1970, sorghum productivity increased annually at 0.96 % per year across the top 10 countries. China (100.9 kg/ha/year) and Nigeria (48.6 kg/ha/year) experienced phenomenal yield gain before reaching a plateau. Overall yield gain was not associated with increased yield stability in a majority of countries except Ethiopia. In fact, in China and India (post-rainy season sorghum), the yield variability increased over time. Genetic gain for grain yield over the years in the Indian sorghum improvement program was prominent in the rainy season (over 18 kg/ha/yr for hybrids and 90 kg/ha/yr for varieties till the 1980s),

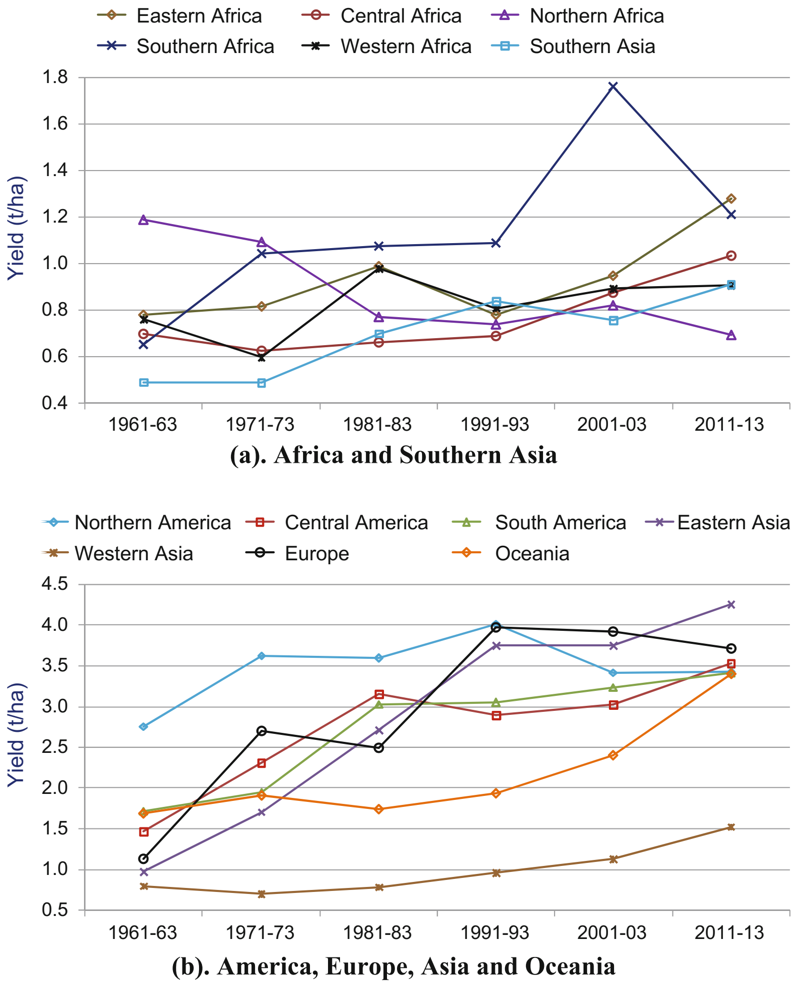

Fig. 3 Global trends in sorghum yield (3-year average, 1961–1963 to 2011–2013)

whereas it was insignificant in the post-rainy season.

6 International Trade

World trade in sorghum is mainly linked to demand for livestock products, which is governed by the feed requirements and prices in developed countries. Only about 6 % of the world sorghum trade is for food use, which is in the form of imports by countries in Africa (ICRISAT & FAO 1996). As the trade is primarily for animal feed, the quantity of sorghum traded depends on the difference in the prices of sorghum and maize and fluctuates considerably. Most of the sorghum is consumed in the countries where it is produced. However, export volumes have increased from less than 3 m t in 1961 to over 13 m t in the early 1980s, peaking at 1981 with 14.48 m t. Substantial expansion took place in the mid-1960s and early 1970s. During this period within a span of roughly 12 years world trade in sorghum almost tripled. This was in line with the rise in imports of other coarse grains as well. The next sharp rise occurred in the early 1980s, when as a result of an export embargo by the United States, the former USSR started purchasing large quantities of sorghum in the international market (ICRISAT & FAO 1996). Exports started declining from 1985 onwards and remained at around 9 m tons until

Table 2 Sorghum yield levels in top sorghum-producing countries[a]

Country	Yield (kg/ha)					
	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013
United States	2756	3624	3596	4013	3416	3431
Nigeria	856	637	1624	1043	1119	1294
Mexico	2347	2601	3491	3317	3214	3762
India	490	485	703	845	762	920
Argentina	1718	1953	3332	3636	5014	4380
Ethiopia	793	950	1462	1402	1280	2169
Sudan	936	776	642	621	688	576
Australia	1693	1912	1738	1938	2402	3400
China	971	1710	2715	3755	3785	3809
Brazil	2500	2232	1952	1740	2044	2721
Burkina Faso	482	471	583	985	938	1016
Niger	675	370	322	165	290	379
Cameroon	858	710	659	765	1317	1456
Mali	681	765	847	829	773	998
World	**932**	**1248**	**1498**	**1380**	**1329**	**1443**

[a]Each figure is a 3-year average for the respective period, for example, 1961–1963

the early 1990s, and then dropped further to 6–7 m tons to a current level of 6.4 m tons (2011–2012 average) valued at US $1657.24 m (Table 3). This decline in export volume and value resulted from a number of factors including a sharp reduction of production in the United States, narrowing of the price gap between maize and sorghum that made sorghum less competitive as a feed ingredient, and the lifting of a ban on maize imports by various countries including Colombia, Mexico, and Venezuela (ICRISAT & FAO 1996).

Argentina, Australia, China, and the United States are the major sorghum exporters, together accounting for more than 90 % of global export volume (Table 3). Sorghum production and export from Argentina increased sharply between the early 1960s and early 1980s, during which the harvested area rose from 0.8 m ha to 1.9 m ha. However, following a drop in demand in the second half of the 1980s, exports declined significantly. With diversion of wheat area to sorghum and matching increase in production, Australia entered the export market at the beginning of the 1970s. By the mid-1980s, China became an important exporter. However, with a sharp rise in domestic demand for sorghum as animal feed, its share in the world market dropped gradually. In fact, currently to meet its domestic demand, China is importing a significant quantity of sorghum from the international market. Some of countries such as India began exporting large quantities of grains over the years, particularly since 2002. Before 2002, exports were inconsistent, which peaked once in 1993–1994, when total production was hovering around 11–12 m t. On the other hand in countries such as Mexico, the export volume was very high in the late 1960s but over time decreased substantially. Other countries including Romania and Venezuela began sorghum exports in the early 1980s and 1990s, respectively. Ukraine and Bolivia are the two countries that started exporting sorghum after 2000, and their volumes are increasing. Countries that had steady exports till the 1980s or 1990s are Sudan and South Africa, whereas Argentina, Australia, and the United States had very high levels of export almost throughout the whole period.

Table 3 Major sorghum exporters by region ('000 tonnes)[a]

	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2012
Africa	**173.25**	**261.45**	**337.59**	**250.55**	**22.37**	**57.32**
Western Africa		**0.17**	**10.90**	**0.03**	**3.57**	**4.58**
Northern Africa	**90.15**	**67.99**	**288.48**	**204.52**	**11.32**	**16.62**
Morocco	8.88	1.08	0.01	0.09		
Sudan (former)	80.80	66.57	288.42	204.43	10.84	27.24
Eastern Africa	**1.83**	**2.99**	**3.23**	**44.31**	**4.80**	**35.01**
Ethiopia		2.98			0.91	16.34
Kenya			1.24	40.28	0.41	0.40
Southern Africa	**81.27**	**190.30**	**34.98**	**1.68**	**2.68**	**1.11**
South Africa	75.93	190.30	34.87	0.86	1.48	0.78
Asia	**0.77**	**137.55**	**286.73**	**441.17**	**57.55**	**149.20**
Eastern Asia		**0.08**	**2.14**	**384.61**	**50.84**	**53.28**
China			2.13	383.66	50.82	53.24
Southern Asia	**0.21**	**7.39**	**0.14**	**7.86**	**5.33**	**94.14**
India	0.01		0.03	7.86	5.07	93.47
Southeastern Asia		**129.16**	**284.39**	**48.54**	**1.28**	**1.77**
Thailand		129.16	245.88	48.15	1.22	1.35
Americas	3048.22	5797.62	11728.21	7808.21	6206.64	4979.77
North America (United States)	**2634.91**	**4111.70**	**6469.56**	**6634.86**	**5583.04**	**2661.66**
Central America	**2.60**	**25.84**	**10.02**	**14.21**	**0.48**	**7.34**
Mexico	0.06	19.50	3.42	13.61	0.01	0.34
South America	**410.71**	**1660.08**	**5248.63**	**1159.15**	**623.12**	**2310.76**
Argentina	410.71	1646.12	5188.72	1138.34	499.82	2282.46
Bolivia			0.21		0.28	12.62
Brazil		13.69	14.69	0.04	104.19	0.23
Uruguay		0.00	45.01	0.32	15.10	15.39
Europe	**62.27**	**201.54**	**237.16**	**265.63**	**238.87**	**221.29**
France	1.00	133.96	192.40	246.99	212.41	81.07
Italy	0.18	0.06	0.14	0.07	6.10	4.53
Ukraine					0.59	89.27
Germany	6.24	0.09	0.05	0.13	0.78	12.27
Netherlands	23.46	54.26	3.14	5.15	11.06	5.22
Hungary			6.47	8.25	1.17	4.95
Belgium	22.50	7.37	26.69	4.73	4.49	1.70
Oceania	**25.61**	**748.59**	**726.20**	**187.33**	**402.04**	**987.96**
Australia	25.61	748.59	726.20	187.33	402.04	987.96
World	**3310.12**	**7146.74**	**13315.89**	**8952.89**	**6927.48**	**6395.54**
World Export Value (million US$)	**140.76**	**480.18**	**1726.21**	**993.38**	**738.55**	**1657.24**

[a]Each figure is a 3-year average for the respective period, for example, 1961–1963, except 2011–2012

Among the African regions the biggest sorghum importer is Eastern Africa followed by Northern Africa (Table 4). In the Americas, it is Central America followed by South America, whereas on the Asian continent Eastern Asia has the largest sorghum importers compared to other regions. Analysis of imports by the different countries indicates that although several countries import sorghum, the bulk of the quantity is concentrated in a few countries such as Japan and Mexico, which account for nearly 75 % of international imports. Another significant importer is the European Union with the Netherlands, Spain, and Belgium importing sizeable quantities. Countries including the United Kingdom, Denmark, Poland, and Germany, which used to import significant quantities have reduced imports over the years. Similarly, countries such as Venezuela, Senegal, Swaziland, Sweden, Yemen, and Zambia, which used to import sorghum in small to medium quantities in the 1960s or 1970s, now only import sorghum in some years. Total sorghum imports worldwide have been falling since the mid-1980s and continue to fall (Table 4). Some of the countries without continuous imports but with very high quantity at certain points of time are Benin (1980–1990), Cyprus (1975–1985), Indonesia (1982–1988), Ireland (1966–1981, 2007–2008), Mali (1988–1994), Singapore (1980–1988), Turkey (1989–1991, 1996–1997), Iran (1975–1979, 1982–1989), and Iraq (1984, 1989–1992). India imported sorghum till 1986 and thereafter it has been almost nil. Some of the countries that started importing in the recent past or post-1980s are China, the Philippines, Morocco, Sudan, Switzerland, Thailand, Tunisia, and Uruguay.

7 Sorghum Grain Composition

The composition of sorghum grain is similar to that of maize or other cereal grains. However, the perceived poor nutritional and processing quality of sorghum is because of the presence of tannins and poor protein digestibility, which affects its use in food and feed. In general, sorghum varieties with a pigmented testa have condensed tannins (Dykes and Rooney 2006). Depending on the presence of tannins or other phytochemicals, sorghum is classified into different types. Sorghums without a testa are generally white, and are preferred for direct food uses, as these sorghums contain the lowest amount of phytochemicals. Other types of sorghum contain a testa but do not have tannins, and may be called yellow, although most have a red-colored appearance. Brown-colored sorghums contain a pigmented testa and condensed tannins, and are generally bird-resistant. Red or brown sorghums have the best nutraceutical potential as they have high antioxidant capacity imparted by phenolics, anthocyanins, and tannins (Serna-Saldivar and Rooney 1995; Rooney and Serna-Saldivar 2000). Sorghums are free of tannin, having nearly the same levels of phytin and phytic acid as maize and other cereals, but digestibility is found to be slightly reduced compared to maize (Rooney 2003). The proximate composition and nutritional aspects of grain sorghum have been extensively reviewed by Hulse et al. (1980), and Subramanian and Jambunathan (1980). The grains are particularly rich in starch (56–75 % of the total dry matter) and soluble sugar, pentosans, cellulose, and hemicellulose are low. Sorghum endosperm contains 23–30 % amylose and 70–77 % amylopectin, but waxy varieties contain less than 5 % amylose (Leder 2004). The soluble sugars range from 0.7 to 4.2 % and the reducing sugars from 0.05 to 0.53 %. Crude protein content in sorghum grain ranges from 9 to 13 % of dry matter and is slightly higher than that of maize. Fat content is slightly lower in sorghum grain (2.1–7.6 %) than in maize. Crude fiber ranges from 1.0 to 3.4 % and ash from 1.3 to 3.3 %. Sorghum grain is devoid of xanthophyllin and 70 % of its phosphorus is bound in phytate (Sauvant et al. 2004).

A comparison of nutrients in various cereals is presented in Table 5. The protein quality of sorghum grain is poor because of the low content of essential amino acids such as lysine (1.06–3.64 %), tryptophan, and threonine (Badi et al. 1990). Sorghum is poorly digested by infants (MacLean et al. 1981), but if it is supplemented with foods high in lysine, can be a satisfactory

Table 4 Major sorghum importers by region ('000 tonnes)[a]

	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2012
Africa	**63.37**	**113.62**	**258.88**	**534.81**	**356.31**	**751.19**
Western Africa	**13.86**	**61.17**	**112.49**	**92.38**	**14.74**	**50.77**
Burkina Faso		0.64	11.15	17.77	0.07	
Mauritania			13.68	5.86	1.30	
Niger	0.03	19.22	24.38	21.67	0.77	27.27
Senegal	13.83	41.31	36.00	17.61	0.01	4.95
Northern Africa	**9.77**		**0.14**	**228.25**	**184.67**	**219.73**
Egypt	9.77		0.01	37.03		30.46
Morocco			0.10	0.26	0.11	38.63
Sudan (former)				189.00	41.40	290.27
Central Africa		**11.67**	**89.91**	**12.31**	**0.14**	**48.26**
Chad		11.67	85.00	5.67		45.99
Eastern Africa	**8.68**	**12.47**	**15.07**	**102.22**	**74.38**	**251.57**
Eritrea				14.57	29.11	27.00
Ethiopia		0.94	4.05	51.55	14.31	39.64
Kenya				17.75	0.16	63.86
Mozambique	1.67			10.30	0.09	1.91
Rwanda			0.07	1.40	0.16	18.50
Somalia	1.00	3.94	7.42	20.58	14.42	28.35
Zimbabwe		5.67	0.00	17.13	7.21	13.71
Southern Africa	**31.07**	**28.31**	**41.26**	**99.64**	**82.39**	**180.86**
Botswana	22.33	15.67	23.54	10.16	40.97	84.07
South Africa	1.57	2.88	11.06	85.81	36.58	91.94
Asia	**614.40**	**4687.00**	**4778.75**	**3655.20**	**1875.15**	**1714.95**
Eastern Asia	**431.96**	**3708.89**	**4160.04**	**3374.44**	**1781.40**	**1632.71**
Republic of Korea	0.09	0.04	213.19	79.64	4.40	5.51
Taiwan		23.24	705.55	58.05	50.46	98.07
Japan	431.87	3685.61	3228.48	3229.15	1724.37	1485.80
China		23.24	718.36	61.18	52.62	141.40
Southern Asia	**3.41**	**395.99**	**86.16**	**4.95**	**10.11**	**0.74**
Iran	0.00	0.04	73.18		10.03	
India	3.28	395.95	11.07			
Southeastern Asia			**54.42**	**3.02**	**6.08**	**21.38**
Philippines				0.37	4.76	15.40
Singapore			34.01	0.46	0.05	0.01
Indonesia			15.80		0.30	4.59
Western Asia	**179.03**	**582.13**	**478.13**	**272.79**	**77.55**	**60.11**
Israel	175.97	576.12	369.96	170.33	71.48	43.81
Americas	**84.17**	**480.73**	**3545.24**	**3988.78**	**4477.99**	**3348.74**

(continued)

Table 4 (continued)

	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2012
Northern America		**0.18**	**0.60**	**2.08**	**5.76**	**19.34**
United States		0.18	0.60	0.72	0.22	15.44
Central America	**78.54**	**102.93**	**2884.38**	**3892.22**	**4377.79**	**2059.72**
Mexico	75.95	92.34	2880.04	3890.75	4376.75	2053.25
Caribbean	**0.22**	**0.29**	**0.04**	**2.34**	**1.91**	**0.07**
South America	**5.41**	**377.33**	**660.22**	**92.14**	**92.53**	**1269.61**
Colombia			89.02	17.88	27.62	550.02
Ecuador			3.33	21.23		22.67
Venezuela	0.76	361.42	558.65	4.68	0.47	0.01
Chile		7.62	6.27	29.23	51.74	616.65
Peru	0.28	5.11	0.30	9.16	0.13	70.80
Europe	**2255.42**	**1177.80**	**4230.75**	**551.64**	**557.26**	**505.85**
France	13.69	3.04	2.41	1.42	1.43	41.97
Italy	0.60	20.37	4.57	93.82	98.92	47.49
Spain	0.76	313.75	732.82	298.53	324.82	235.39
United Kingdom	408.25	108.96	4.12	2.41	5.16	10.14
Netherlands	701.06	195.98	57.37	31.86	23.14	23.99
Belgium	514.15	263.46	171.14	92.33	44.39	48.69
Denmark	224.78	1.26	0.13	0.17	0.61	1.85
Norway	62.48	37.43	134.91	0.02	32.08	2.68
Portugal		78.08	189.47	1.76	11.60	14.30
Poland	163.57	21.80	0.00	12.29	1.33	7.69
Germany	136.66	57.64	11.39	8.58	8.96	65.11
Oceania			**10.95**	**10.96**	**58.83**	**82.88**
New Zealand			1.50	0.01	26.43	63.24
Papua New Guinea			9.44	5.67	32.14	19.00
World	**3017.36**	**6459.15**	**12824.57**	**8741.38**	**7325.54**	**6403.61**
World Import Value (million US$)	**162.00**	**504.37**	**1820.75**	**1088.72**	**945.86**	**1896.80**

[a]Each figure is a 3-year average for the respective period, for example, 1961–1963, except 2011–2012

weaning food (Badi et al. 1990). Sorghum proteins become less digestible after cooking (Actell et al. 1981; Eggum et al. 1983; Duodu et al. 2003) due to change in the structure of kafirin present in grain protein. Sorghum is a good source of minerals and B vitamins such as thiamin, riboflavin, vitamin B6, biotin, and niacin, but refining leads to losses of all B vitamins (Hegedus et al. 1985). The chief minerals present in sorghum grain are potassium and phosphorus, whereas calcium is low (Khalil et al. 1984).

Sorghum is a rich source of various phytochemicals including phenolic compounds, anthocyanins, phytosterols, and policosanols that are secondary plant metabolites or integral cellular components (Awika and Rooney 2004). Phenolic compounds can be classified as phenolic acids, flavonoids, and condensed polymeric phenols (flavan-3-ols) known as tannins. Condensed tannins decrease the nutritional value of the sorghum grain because they bind to dietary proteins, digestive enzymes, minerals such as