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Review

Challenges for Crop Production Research in Improving Land Use, Productivity and Sustainability

Huub Spiertz

Center for Crop Systems Analysis, Plant Sciences, Wageningen University, P.O. Box 430, Wageningen 6700 AK, The Netherlands; E-Mail: huub.spiertz@wur.nl

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Abstract: The demand for food, feed, and feedstocks for bioenergy and biofactory plants will increase proportionally due to population growth, prosperity, and bioeconomic growth. Securing food supply and meeting demand for biomass will involve many biological and agro-ecological aspects such as genetic plant improvement, sustainable land use, water-saving irrigation, and integrated nutrient management as well as control of pests, diseases and weeds. It will be necessary to raise biomass production and economic yield per unit of land—not only under optimum growing conditions, but even more under conditions constrained by climate, water availability, and soil quality. Most of the advanced agronomic research by national and international research institutes is dedicated to the major food crops: maize, rice, wheat, and potato. However, research on crops grown as feedstock, for bio-energy and industrial use under conditions with biophysical constraints, is lagging behind. Global and regional assessments of the potential for growing crops are mostly based on model and explorative studies under optimum conditions, or with either water or nitrogen deficiencies. More investments in combined experimental and modeling research are needed to develop and evaluate new crops and cropping systems under a wide range of agro-ecological conditions. An integral assessment of the biophysical production capacity and the impact on resource use, biodiversity and socio-economic factors should be carried out before launching large-scale crop production systems in marginal environments.

Keywords: agricultural research; biomass yield; bioenergy; cropping systems; crop adaptation; food security; nutrient management; water saving

1. Introduction

1.1. Crop Productivity and Food Security

The general trend in global food security during the second half of the last century was characterized by a change from shortages to surpluses, resulting in food affluence in the developed world. From the mid-1960s to the end of the 1970s new technologies and innovations, including the choice of semi-dwarf cultivars, split dressings of nitrogen, use of growth retardants, and the use of systemic fungicides and insecticides were introduced in wheat cropping systems to enhance yields. In irrigated rice systems the introduction of high-yielding hybrids combined with ample nitrogen supply did boost yields. There is substantial evidence that the so-called "green revolution" resulted in improved crop yields of the three major grain crops: maize, rice, and wheat [1]. During the last three decades the emphasis was shifted to reducing the side effects of external inputs in intensive farming systems. As a consequence, the external inputs (e.g., nitrogen and biocides) were reduced, and crop yields reached a plateau. However, food scarcity continued to persist for poor people in developing countries with a still fast growing population and often also political instability [2]. Estimates of the number of people suffering from hunger and poverty decreased to about 800 million in the period from 1985 to 2005, but showed a rise to about 1.2 billion afterwards, due to price volatility and regional food shortages. Besides political and socio-economic constraints the following also play a role: a lack of legislation, a change of food preferences, occurrence of animal and crop diseases, climate change induced weather extremes, an increased scarcity of resources (irrigation water, phosphorus, fertile land), and rising costs of fossil energy [3].

The demand for food and feed is not only driven by a growing population, but even more by diet choice, food waste, and lifestyle (e.g., easiness). Misselhorn *et al*. [3] also stress that global food security is closely linked to human development. Globally, food demand will increase by 50% and the area of cultivated land by 10% by 2030 [4,5]. Adaptive and proactive food systems are needed with cross-level, cross-scale, and cross-sector investments and use of frontier technologies to attain food security.

1.2. Biomass Production and Energy Security

A major transition from fossil fuel sources to renewable energy sources in a relative short time spell—less than four decades—is needed to meet the standards for reducing GHG-emissions. The benefits of bioenergy for society were summarized by Valentine *et al*. [6] in four terms: a) reduction of C emissions, b) contribution to energy security, c) incentives for rural and urban economic development and d) dependence of global agriculture on fossil fuels. They concluded that these goals could be best fulfilled by growing dedicated perennial bioenergy crops. This may be true for the tropics and regions with a temperate climate, however in more continental regions with cold winters, frost damage will prevent the growth of perennial crops.

The potential for sustainable bioenergy production is estimated at 340 EJ a^{-1} in 2050, when all sources (bioenergy crops, residues and waste, algae, *etc*.) are used [7]. In those scenarios, the area of land needed for bioenergy crops would be 250 million ha, which is about one third of the land potential that can be used in a sustainable way. An interesting case is China, a large country with a huge population (1.3 billion), limited area of agricultural productive land, and a fast economic growth for more than 20 years. China's bioenergy potential was explored by Sang & Zhu [8]; they concluded that 300 million tons of crop residues, mainly from maize, rice and wheat, would be available for electricity generation. The development of second generation energy crops holds the greatest potential [8]. The production capacity of *Miscanthus*—annually grown at about 100 million ha of marginal or degraded land in northern and northwestern China—is estimated at one billion tons of biomass. This amount of biomass corresponds to about 1500 TW h electricity, or 45% of the current power capacity, which would mitigate CO_2 emissions from coal by almost 30%. A GIS-based study of the availability of crop residues derived from all crops in China was carried out by Jiang *et al*. [9]. In their assessment, they estimated net available crop residues of about 500 million tons per annum, which corresponds with about 250 million tons of coal (7.4 EJ a^{-1}), accounting for about 8% of the total energy consumption in China. To estimate the area of degraded land, Nijsen *et al*. [10] used the Global Assessment of Land Degradation Dataset. This area was converted into a global potential for energy production. These types of explorations are valuable desk studies, but a thorough experimental validation will be needed.

The assessment of multi-annual crop performance as monocrop, or in a crop rotation under contrasting agro-ecological conditions will provide data to quantify production-ecological attainable yield levels. Furthermore, net energy gain in the production chain and environmental impact are important criteria to evaluate the profitability and sustainability at a local and regional scale before launching large-scale production of bioenergy crops [11,12].

1.3. Agriculture and Land Use

Globally, we have taken about 26% (3.3 billion ha) of the planet's land area for crop land and pasture. The pressure on fertile land does vary for different parts of the world: relatively low in Europe and Latin America, compared to South-East Asia where the available fertile land per capita decreased to <0.20 ha [13]. The pressure on land has intensified over the last 40 years in Asia because of the growth of the already high population density in regions with fertile land. Assessments of land use should be scientifically sound and not be guided by ideologically based parameters, like a globally "fair share" of acceptable resource use as proposed by Bringezu *et al*. [14]. They concluded that, on average, the countries in the European Union use one-third more crop land than globally available per capita, and thus exceed the criterion of "fair share". However, it had already been shown in the study "*Ground for Choices*" some 20 years ago, that Europe has a surplus of arable land [15]. The more fertile and productive land has already been brought into exploitation for agriculture and grazing in the past—in Europe, since the 12th Century [16]. Generally, the driving forces for land reclamation from the sea (polders), cutting forests and converting grazing land have been the growing demand for food and, more importantly, creating employment and income of a growing rural population. In the USA, the economic-based 'right to farm' was more important for expansion of agricultural land use than environmental concerns, such as long term consequences for soil carbon storage and overuse of limited water reserves (aquifers, rivers, *etc*.) [17].

The growing demand for food and green feedstocks for bioenergy, chemicals, and material will lead to an expansion of agricultural land, more use of fresh water, fertilizer nutrients and, last but not least, an increase of the use biocides (herbicides, fungicides and pesticides). Wolf *et al.* [18] projected that only 55% of the present agricultural land area would be needed for food production in 2050 if high external inputs systems are applied. The remaining 45% can then be used for other purposes, such as bioenergy production. However, if low external input cropping were applied on a global scale, no land would be left for biomass production. Unfortunately, this study does not take into account the negative impact of higher emissions in systems with high external inputs on the environment, as was shown for the European Union [19].

Currently, the concerns of scientists for impending land use changes in developing and new industrialized countries—like China, Brazil, and Indonesia—are growing [20]. The expansion of soybean production in Argentina is one of the recent examples that low productive land (extensive grazing land: Pampas) can be reclaimed and transformed in highly productive agricultural land. Caride *et al*. [21] reported a positive SOC balance—a 10% increase over 60 years—for a cropping rotation of soybean or wheat, soybean double crop (six years) and pasture (four years) under no till and high fertilization. At a regional scale, the loss of SOC averaged 15% over 60 years when crop sequences were not adapted. However, the long-term impact of the conversion of grazing to arable land on the flora and fauna is only partially understood. It was found that biofuel-driven growth in corn planting results in lower landscape diversity, altering the supply of aphid natural enemies to soybean fields and reducing bio-control services [22].

2. Constraints and Opportunities in Increasing Land Availability

In the future we will face greater complexity. Meeting food security and biomass feedstocks will involve many biophysical and ecological aspects such as genetic plant improvement, sustainable land use, water saving irrigation, integrated nutrient management, and control of pests, diseases and weeds. Furthermore, socio-economic factors (poverty, affluent societies) and consumer behavior (change of diets, fast versus slow food) are already playing a major role in a more urbanized world [23]. Within 20 years about 70% of the world population will live in cities, which will depend more for food security on global trade than on local or regional production capacity. For the most important commodities prices on the world markets will become more important. Therefore, with the growing urbanization the availability of land is not a regional or even national issue but has to be addressed at a global scale. Land use change through population growth, agricultural intensification and urbanization has also transformed natural ecosystems locally, regionally, and globally. Thus, more emphasis is needed on sustainable use of land, taking into account ecosystem services and prevention from polluting emissions to the environment [24]. A more efficient use of natural resources (solar radiation, water, nutrients, *etc*.) and an improved crop productivity are key features [25].

Availability of fertile land and crop productivity are the most important factors among parameters determining the supply of food and feedstocks for bioenergy and industrial uses [26]. Meeting the demands for food and bioenergy in a sustainable way, we should develop cropping systems that are highly productive, but also robust with respect to abiotic and biotic stresses. Short rotations are, in general, less robust, due to yield declines caused by biotic factors such as plant pathogens, deleterious rhizosphere micro-organisms, mycorrhizas, *etc*. [27]. The effects on yields are mostly more severe when abiotic and biotic factors interact. The benefits of a wider rotation, and even combining food and bioenergy crops, were shown for cropping systems in the European Union [28].

Land availability for food has been considered over the last three decades to become scarce, but at the same time there are a number of reports that show that more land is, and can be, reclaimed for food and feed production. This is especially the case in large parts of Africa, Latin America and Eastern Europe (including Russia). Furthermore, quite a number of studies have been carried out to analyze the availability of marginal or degraded land that might be available for growing green feedstock [29]. Not surprisingly, most of the potential energy crop production on degraded land is located in regions with less developed agricultural production systems. However, there is a trade-off between crop productivity of marginal lands and soil quality. It was found that net primary productivity was inversely related to Land Marginality Index (LMI) and positively to the soil quality index (SQI) [30]. Thus, water and nutrient demands of bioenergy crops grown on marginal land is closely linked to land quality.

A further expansion of the exploitation of marginal and degraded land for bioenergy and industrial feedstocks, as well as the intensification of crop production for food and feed on existing agricultural land, will require more external inputs such as irrigation water, macro-nutrients (N, P, K), and biocides (herbicides, fungicides, and pesticides). Most critical are water scarcity in regions that depend on stored water reserves (aquifers) and the looming shortage of phosphorus reserves. Land use change does impact soil phosphorus status: soil phosphorus content was elevated after abandonment as crop land or pasture [31]. This finding may be important for restoring natural vegetation, but at the same time it indicates that conversion of marginal land into biomass production for bioenergy will require phosphorus supply by fertilizer or manure [32].

3. Prospects for Improving Productivity of Plant Production Systems

New concepts in exploiting promising germplasm and managing crops are needed to optimize yields within environments constraint by soil and weather conditions, and scarcity of external inputs such as water and nutrients (P, N and K). Crop performance can be changed by modifying genetic traits of cultivated plants through breeding and selection. A better quantitative understanding of Genotype x Environment x Management (G x E x M) interactions will accelerate the adoption of better adapted food, feed, and bioenergy crops in target environments. Progress in improving productivity of plant production systems should be made at three levels [26]:

(1). At the *plant/crop* level:
- Improving resource capture and use efficiency, especially for water and nutrients.
- Improving the adaptation of crops to climate change, especially to extreme weather conditions.

(2). At the *farm* level: a greater diversity of cropping systems to enhance ecological processes that contribute to short term yield stability and long term productivity and sustainability.

(3). At the *landscape and regional* level: integrating biophysical and socio-economic research on productivity and sustainability of cropping systems, taking into account land use and global change.

Plant system research has provided insight into factors causing the gap between potential and actual yields [33]. Because of the large variation in agro-ecological conditions, model based explorative studies should be complemented by field-based experimental research. A wide range of crop species and adapted cultivars should be tested under the best agronomic practices.

There is clear evidence that sugar cane and palm oil perform best for bioethanol and biodiesel production respectively [12,34]. However, a further expansion of land to grow these tropical crops/plantations is limited by concerns over biodiversity and aquatic coastal ecosystems. So, it will be necessary to explore options for growing bioenergy crops on land not currently used for food production and with less impact for fragile and unique ecosystems. For example, the exploitation of marginal land with a low inherent productivity and a high risk for agricultural production is an option. Some studies indicate that 300–700 million ha of abandoned and degraded crop land could be developed, and even 1,100 to 1,400 million ha when low-productive grassland, savannahs and shrubland are included [29]. Harvesting abundant sunshine to produce high biomass yields by introducing short-season cropping systems in arid continental environments is a big challenge. Maximizing light capture and use efficiency are key in crop management [35].

A quantitative system approach is needed to perform integrated assessments of sustainability, resource-use efficiencies, ecological services, and economic profitability to guide the choice of crop species and cultivars to be grown in a target environment and region [36]. Generally, biofuel crops like switchgrass and *Miscanthus* have much higher net primary production than food crops (wheat and soybean) [37]. Young and Somerville [38] showed quite an optimistic outlook by stating that in some C_4 crops, such as *Miscanthus*, biomass yields can further be improved without an increase in external inputs (nitrogen, water, *etc*.). Furthermore, they hypothesize that by preventing flowering, plants would remain vegetative, thereby extending the period of biomass accumulation. Considering that high-yield crops are often more sink than source limited, this hypothesis should be thoroughly examined. A better quantitative understanding of G x E x M interactions of dedicated bioenergy crops in target environments will show if the hypothesis is valid. To understand G x E x M interactions in a quantitative way, there is a need for statistical and modelling tools that can support breeders, agronomists, and farmers to develop new high-yield cropping systems that are not only efficient, but also sustainable.

Meeting the growing demands for food, feed, and bioenergy feedstocks at present and in the future will require a further strengthening of research capacities in plant sciences, crop improvement, and agronomy. An assessment of research investments in various fields can be made by taking the number of publications in international refereed journals as a proxy value [39]. The imbalance in research funding for food and bioenergy crops is shown by comparing the number of publications in the period 2002–2012 with the acreage and production value of a selection of crops (Table 1). Currently, the research capacity for bioenergy crops is lagging behind those for food and feed crops. To make proper assessments of the potential to grow bioenergy crops without competing for fertile land dedicated to food crops, it will be necessary to strengthen the capacity of the research chain from the lab to the field, farm, and processing plants [40]. Erb *et al.* [41] concluded that the design of future crop production policies needs to resolve trade-offs between food vs. energy supply, renewable energy vs. biodiversity conservation and increasing yields vs. environmental problems. Some authors argue that less government interference with the implementation of environmental goals will enhance ecological and economic benefits [42]. The bio-based economy, however, has already led to new production systems, crops and products for industrial use; in some countries in south-east Asia and South America it shows double digit growth rates [43]. Currently, ‘green policies’ aimed at renewable energy are advocating bioenergy production at the expense of biodiversity and/or food production without a clear understanding of the trade-offs. A novel hybrid approach for assessing sustainability trade-offs was recently proposed by Acosta-Michlik *et al*. [44]. They combine empirical techniques, fuzzy logic and path analyses for a systematic investigation of trade-offs. Integrated dual use farming for sustained food security and agro-bioenergy development was suggested by Mendu *et al*. [45]. Their concept was illustrated by the use of high-lignin agricultural residues, such as endocarp biomass, for small-scale gasification to produce electricity in rural areas where people lack basic access to electricity and rely on solid fuels (coal, manure, *etc*.), causing health problems. Taking into consideration the world-wide growing demand for food, feed, and bio-based products (bio-energy, industrial use, *etc*.), it will be necessary to raise the production per unit of land and external input under well-endowed conditions, as well as under so-called marginal conditions. The latter conditions are less suited to food production because of the higher risks of drought and heat during the reproductive period. The risks are much lower when crops are grown for biomass accumulation as a feedstock for bioenergy. Furthermore, the plant protein production should be boosted to meet the demands for animal feed on a regional scale, as well as to reduce the dependence on fertilizer nitrogen [46].

Table 1. Acreage and production value of crops in 2010 and total number of papers per crop published from 2002 to 2012.

Crops	Acreage*	Production value*	Publications**
A. *Food Crops*	(10^3 ha)	(10^6 USD)	(number of papers)
Wheat	216,974	81,236	14,947
Rice	153,652	174,747	8,257
Soybean	102,387	64,859	6,052
Potato	18,596	44,519	3,155
B. *Dual purpose crops*			
Maize	161,908	55,146	8,021
Sugar beet	4,676	9,220	1,109
Palm oil	NA	(41.700)	841
C. *Energy crops*			
Sugar cane	23,815	53,639	679
Sweet sorghum	NA	NA	210
Miscanthus	NA	NA	266
Switch grass	NA	NA	40

* Source: FAOSTAT; ** Source: Web of Science; NA = not available; ( ) World oil consumption in 2009 in million ton [41].

4. Institutional Change and Development

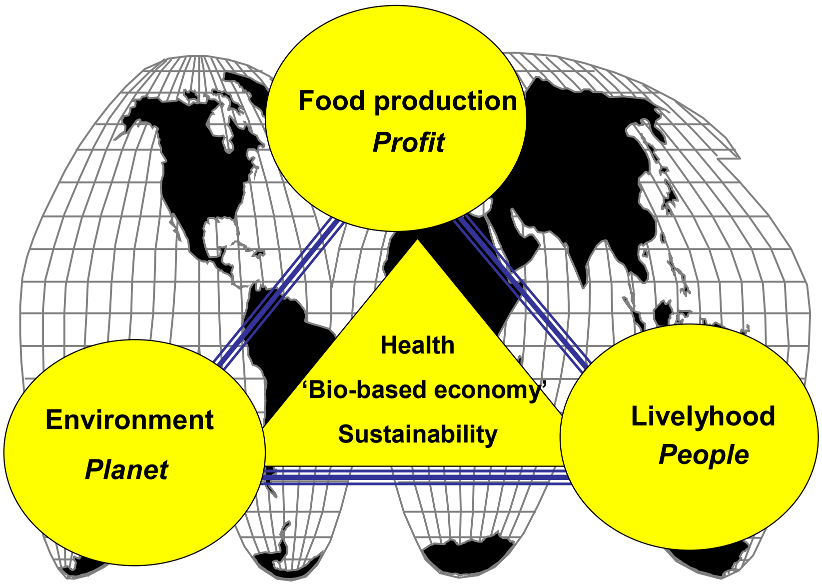
The role of crop sciences in providing the key knowledge base for increasing the production and quality of human food, animal feed, and biomass for industrial use and the provision of energy was already emphasized in the Declaration of Hamburg at the occasion of the Third International Crop

Science Congress in 2000 [47]. Scientists expressed their concerns over the lack of awareness of the gravity of food security and poverty issues on the global level, the urgency of protecting genetic resources and biodiversity, and the scarcity and degradation of natural resources such as land and water. Strengthening agricultural research and education at a national and international level was considered to be a prerequisite to fulfil future human needs. There is a big gap in research funding by developed and developing countries. The fundamental role that agriculture plays was also emphasized by Byerlee *et al*. [48]. They concluded that globalization, integrated value chains, rapid technological and institutional innovations, and environmental constraints have changed the context for agricultural development. In their vision, governments and donors neglected agriculture's multiple functions (providing food security, reducing rural poverty and environmental services), with the result that agriculture growth has been reduced, and food insecurity has returned without saving on natural resources (water, land, nutrients), thus comprising sustainability. My quick scan of crop acreage, production value, and scientific output reveals that the majority of the shrinking investments in agriculture research is allocated to major food, feed, and biofuel crops: wheat, rice, maize, soybean, and potato.

There are two main roads for agronomists and plant breeders to improve the crop performance: a) to improve yields and resource use efficiencies by introducing new technologies and farming practices and by minimizing the effects of abiotic stresses, and b) to exploit new knowledge on genetic traits and physiological relationships in advanced breeding programs for genotypes that are tolerant to multiple stresses (drought, heat, salinity, *etc*.). These roads cannot only be paved by the private sector: there is also an important role for the public sector. Governments should provide the infrastructure for fundamental research and academic training of a future generation of scientists who are able to meet the future challenges. A stronger linkage between research and innovation can accelerate the dissemination and implementation of the new knowledge needed to develop highly productive and sustainable plant production systems. The new EU-Framework program Horizon2020 (2014–2020) presents an example of research funding that strengthens the public research capacity of 27 EU countries, as well as cooperation with research institutions in the private sector. A budget of 80 billion Euros will be available for six main themes: health, demography, food security, sustainable agriculture, maritime and marine research, and bio-economy.

At the global level, funding of the research centers of the Consultative Group on International Agricultural Research (CGIAR) has been declining since the success of the Green Revolution, with abundant food supplies at low costs [49]. In response, a more intensive cooperation within the CGIAR system has been established, for example, the CRISP program for rice research. Zeigler and Mohanty [49] discussed also the nature of the financial support: unrestricted vs. project specific grants. The transition from unrestricted input funding to competitive program or project specific grants has also been taking place in Europe since the mid-1980s. Long-term unrestricted funding since the mid-1960s has made great leaps forward possible in genetics, breeding of semi-dwarf, highly productive rice and wheat cultivars, in the development of mechanistic soil and crop growth models, and the development of sensors for monitoring crops and soils. These technologies made it possible to develop decision support systems for precision farming. A problem for governments and private funding agencies is the lag time between new findings by basic research and its impact on improving crop productivity and farming systems. From funding agencies if requires a strategic vision, and future-oriented decision making that considers critical mass in research capacity. A realistic time span should be allowed for new findings to mature and become available for developments and innovations. My personal view is that high quality academic and strategic research requires a sound balance between unrestricted (long term, 5–10 years), program (mid-term, 3–4 years), and project (short term 1–2 years) funding. The split of the total budget over these categories will depend on the strategic view of policymakers, donors, and private industry.

Figure 1. Framework to relate sustainability, bio-based economy, and health goals with boundaries for objectives in the domains of *People, Planet & Profit* (after: [50]).



In The Netherlands, top institutes were established by the government, university, and industry to strengthen research capacity in specific strategic fields (e.g., Food and Nutrition, Green Genetics, and Climate Change). These investments strengthen pre-competitive research, which may accelerate spin-offs for applied research, innovations, and applications [50]. There is no single unique concept for solving problems in meeting the demands for primary agricultural products because of the contrasting conditions (biophysically, biological, socio-economic and political) between countries and agro-ecological regions. However, lessons should be learned from the past. Timely investments in research are needed to solve the problems in food security, sustainability and the well-being of the next generation. Not only the level of national research funding, ranging from 0.5% (Mexico) to 4.0% (Finland) of the Gross National Product, but also the institutional arrangements matter. Good examples are presented by Robert Herdt [51], who referred to policy change by the Rockefeller Foundation in the mid-1990s which went from funding national research centers towards funding of large networks, e.g., the international rice biotechnology network. Some scientists made a plea for "innovation-ecosystems": a network of top institutes, universities, industry, and stakeholders. Large funding agencies are needed to launch research programs that might have impact in solving food security and sustainability problems. A new player in funding agricultural research in developing countries, especially Africa, is the Gates Foundation. Their programs cover the spectrum of strategic research, applied research, and extension to solve specific problems in food security (N2Africa) and human health.

5. Conclusions

It is well known that the demand for agricultural products will increase proportionally to population growth and prosperity. Assessments of the balance between the attainable plant production and the demand for plant produce at regional and global scale are fundamental to developing strategies for food security and meeting the demand of a more bio-based economy. The latter requires more research capacity to develop new crops and cultivars that are adapted to multiple stresses (drought, heat, *etc.*) and are more resource efficient. New cropping systems are needed that increase land productivity, but also maintain their resource base (soil quality, soil health, ecosystem health) and facilitate biodiversity in agricultural landscapes.

The ultimate objective is to combine food security and the supply of feedstocks for bioenergy and biofactory products in a sustainable and cost effective way at a regional and global scale (Fig 1). More strategic and applied research should be carried out to develop sustainable cropping systems, which are adapted to less favorable agro-ecological conditions. Most of the advanced agronomic research by national and international research institutes is dedicated to the major food crops: maize, rice, wheat, and potatoes. However, research on crops grown as feedstock for bio-energy and industrial use under conditions with biophysical constraints is lagging behind. More investment in combined experimental and modeling research are needed to develop and evaluate new crops and cropping systems under a wide range of agro-ecological conditions.

Conflict of Interest

The author declares no conflict of interest.

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