Bogdanski *Agriculture & Food Security* 2012, **1**:9
http://www.agricultureandfoodsecurity.com/content/1/1/9

Agriculture & Food Security

REVIEW

Open Access

Integrated food–energy systems for climate-smart agriculture

Anne Bogdanski*

Abstract

Food production needs to increase by 70%, mostly through yield increases, to feed the world in 2050. Increases in productivity achieved in the past are attributed in part to the significant use of fossil fuels. Energy use in agriculture is therefore also expected to rise in the future, further contributing to greenhouse emissions. At the same time, more than two-fifths of the world's population still depends on unsustainably harvested wood energy for cooking and heating. Both types of energy use have detrimental impacts on the climate and natural resources. Continuing on this path is not an option as it will put additional pressure on the already stressed natural resource base and local livelihoods, while climate change is further reducing the resilience of agro-ecosystems and smallholder farmers. Ecosystem approaches that combine both food and energy production, such as agroforestry or integrated crop–livestock–biogas systems, could substantially mitigate these risks while providing both food and energy to rural and urban populations. Information and understanding on how to change course through the implementation of the practices outlined in this paper are urgently needed. Yet the scientific basis of such integrated systems, which is essential to inform decision-makers and to secure policy support, is still relatively scarce. The author therefore argues that new assessment methodologies based on a systems-oriented analysis are needed for analyzing these complex, multidisciplinary and large-scale phenomena.

Keywords: Food security, Energy access, Climate-smart agriculture, Mitigation, Adaptation, Ecosystem services, Landscape approach, Integrated food–energy systems, Multi-purpose farming systems, Agroforestry, Biogas, Agro-ecology, Systems thinking approach, Upscaling

Review

Smallholder agricultural production systems are the main source of food and income for most of the world's poorest people, in both rural and urban areas. Improving these systems is critical to global poverty reduction and achieving food security objectives [1,2]. The world counts 1 billion hungry people today and the population is projected to reach 9 billion by 2050, thereby increasing food demand. Food production needs to increase by 70%, mostly through yield increases [1]. Increases in productivity achieved in the past are attributed in part to the significant use of fossil fuels, contributing to greenhouse gas (GHG) emissions and wasting considerable amounts of energy along the chain. Globally, food and agriculture consume 30% of the world's available energy, and produce about 20% of the world's GHG emissions [3].

Productivity increases have often been accompanied by negative effects on agriculture's natural resource base, to such an extent that it could affect its productive potential in the future. This situation is further compounded by climate change impacts reducing the resilience of agro-ecosystems. Managing climate risks while improving resource-use efficiency and productivity of agro-ecosystems are therefore essential in order to reach food-security objectives. These are the main goals of climate-smart agriculture, while the reduction of global GHG emissions is a welcome co-benefit.

This paper aims to describe the unique role that energy contributes to addressing some of the combined challenges related to food security and climate change. Contrary to the majority of recent literature, this manuscript will look beyond the current discussion on liquid biofuels for transport and their potential impacts on

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Correspondence: Anne.Bogdanski@fao.org
Climate, Energy and Tenure Division, Food and Agriculture Organization of the United Nations (FAO), Via delle Terme di Caracalla, 00153, Rome, Italy

food security. The paper will give an overview of different options that allow for the joint production of food and energy in a climate-smart way, and will explain how such integrated food–energy systems (IFES) can contribute to improved food security, energy access and adaptive capacity to climate change. Drawing from case studies, the author lays out the next steps that are necessary to mainstream successful IFES into common practice, while also discussing current barriers that prevent the upscaling of such diverse and integrated systems.

Energy in the context of food security and climate change

Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life [4]. The provision of safe and nutritious food (for example, cooked meals and boiled drinking water) requires one crucial input: energy. Without access to energy there is no food security. Few of the principal food crops in developing countries are palatable or even fully digestible unless cooked. If the cooking time is reduced because of lack of fuel, protein intake is often lowered. In many areas, families can eat only one cooked meal a day instead of two simply because they lack fuel. Furthermore, the production of food requires high energy inputs that, in modern agriculture, are often achieved through fossil-fuel intensive external inputs such as synthetic fertilizers and fuel for on-farm machinery.

Considering this important role of energy in food production and consumption, energy is a crucial prerequisite for resilient livelihoods, strongly contributing to the adaptive capacity of rural communities in light of climate change. Adaptive capacity is ‘the ability of a human or natural system to adapt, i.e. to adjust to climate change, including to climate variability and extremes; prevent or moderate potential damages; take advantage of opportunities; or cope with the consequences. The adaptive capacity inherent in a human system represents the set of resources available for adaptation (information, technology, economic resources, institutions and so on), as well as the ability or capacity of that system to use the resources effectively in pursuit of adaptation’ ([5], p. 9).

While there are currently no *direct* ways to measure adaptive capacity, studies often refer to the asset base as one key indicator for adaptive capacity; that is, the availability of key assets that allow the system to respond to evolving circumstances [a] [6]. Energy forms a vital part of such key assets, as the lack of availability and access to energy can considerably limit the ability of a system to cope with the effects of climate change and wider development pressures.

Nevertheless, the importance of energy for food security and the adaptive capacity of smallholders have still not been recognized widely. Energy, so vital for food security and resilient livelihoods, is often dealt with as a separate issue. This has detrimental impacts, especially for the two-fifths of the world’s population who still depend on traditional bioenergy sources such as fuelwood, charcoal and animal dung for cooking and space heating [7].

Unless food and energy production are well balanced within the agro-ecosystem, energy remains just another external input for smallholder farming systems. In many situations, this means that women and children need to spend hours collecting fuelwood. In other cases, it means high expenditures for charcoal. In Zaire, for instance, the cost of charcoal amounts to about one-third of a worker's monthly wage, and in the poorer parts of the Andean Sierra and in the Sahel one-quarter of all household income must be spent on fuelwood and charcoal [8]. Where fuelwood sources are already fully depleted or out of reach, people rely on crop residues or animal dung for cooking and heating, leading to soil depletion and reduced productivity as a result of removing the nutrients found in such residues.

In fact, the most important type of bioenergy has been and continues to be wood fuels, which in the developing countries generally represent approximately 15% of total primary energy consumption, although this figure conceals differences at the subregional and national levels [9]. Worldwide, there are 34 countries where wood fuel provides more than 70% of all energy needs, and in 13 countries it provides 90% or more [9]. Africa is the region where wood fuel plays its most critical role. In many of these countries, in both rural areas and cities, people not only experience food famines but also fuelwood famines. In many cases, wood fuels, especially charcoal, are also a significant source of income for many people.

Heavy reliance on wood fuels in developing countries has severe implications for forests and climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change indicated that the total carbon content of forest ecosystems has been estimated at 638 Gt [10], which exceeds the amount of carbon in the atmosphere. The Intergovernmental Panel on Climate Change further estimates that 17.4% of global GHGs comes from the forest sector, in large part from deforestation in developing countries [10]. Tropical deforestation globally resulted in the release of an estimated 1.1 to 2.2 Gt/year in the past decade; forest degradation is thought to have resulted in similar emissions, but the data are more limited [11].

While wood fuel materials are obtained from many supply sources – not only from forest lands, but also from dead wood, dry branches and twigs and trees, shrubs and bushes outside forests – wood fuel use and, particularly, charcoal-making contribute significantly to deforestation and forest degradation. Geist and Lambin analyzed 152 cases of deforestation throughout the world [12]. In 28% of the cases reviewed, wood fuel was the primary driver of deforestation[b] In Africa this figure rises to 53% of all cases, showing the utmost importance of wood fuels for cooking and for food security.

At the same time, climate change and increased climate variability will enhance the pressure on agricultural production systems and forests, and thus important sources of energy for many of the world's poor, making people more vulnerable if no adaptation practices are implemented. The additional impacts of rising energy costs and price volatility aggravate this situation, lowering people's adaptive capacity to climate change because energy is directly and indirectly embedded in food production and preparation. At the same time, increased dependence on energy, particularly fossil fuels, for food production will increase climate change, thereby closing the vicious cycle.

The commercial production of nitrogen fertilizers, for instance, accounts for 1.2% of total world energy use, as well as 1.2% of global anthropogenic GHGs [13]. A US Department of Agriculture report stated that the sharp increases for ammonia prices paid by farmers (from $227 per ton in 2000 to $521 per ton in 2006) were strongly linked to increasing prices of natural gas, the main input used to produce ammonia [14].

In light of the above it becomes clear that bioenergy and food provision cannot be addressed in isolation from each other and the environment on which they depend. They need to be equally addressed to strengthen people's adaptive capacity to climate change. Yet at the same time, both food and bioenergy production and consumption can have detrimental impacts on ecosystems, on which rural livelihoods depend, if not adequately managed.

There are many different ways to produce both food and energy in a sustainable way, to enhance people's adaptive capacity and to take the pressure off forests; for instance, through an ecosystem approach that has been documented by a recent Food and Agriculture Organization of the United Nations (FAO) initiative on IFES [15]. This study found that when food and energy production is well balanced within an agro-ecosystem, whether at the local scale or through the division of labor and agro-ecological production functions at a landscape level, many risks can be substantially mitigated. To manage risks, a deeper understanding of the agrotechnological aspects of the system is required, in addition to the social, institutional and policy requirements for implementation. The next section will present different cases of food–energy integration, followed by an overview of those factors that are key to upscale such integrated approaches and pointing to potential barriers.

Sustainable energy options in the rural sector: integrated food–energy systems

Growing fuelwood on-farm

Many smallholder farmers in the developing world practice integration of food and energy production daily within various diversified and integrated farming systems [16]. Simple diversification and integration of food and energy production at the field level have been successfully demonstrated and have resulted in wide-scale dissemination of these farming systems throughout the world. A range of agricultural practices and production systems such as intercropping, organic agriculture, conservation agriculture, integrated crop–livestock management, agroforestry and sustainable forest management activities have proven to protect or even enhance ecosystem services at the local or landscape scale, while producing food, feed and wood products. In many of these systems, excess agricultural/woody residues are available that can be used for energy. Examples of residue use include feeding byproducts to livestock, using residues as food complements, composting to serve as fertilizer inputs and, last but not least, the provision of fuelwood.

Such product diversification can substitute costly, external inputs, saving on household expenditures – or even lead to the selling of some of the products, providing the farmer with extra income, leading to increased adaptive capacity. Seen from the biophysical side, diversified land-use systems protect and promote a variety of different ecosystem services simultaneously and are therefore more resilient and capable to adapt to a changing climate than monocultures. A highly diverse genetic pool and pool of species is better equipped to reorganize after disturbances such as increased floods or prolonged droughts that are expected to occur with climate change [17].

At the same time, many such integrated systems, particularly those including perennials, increase carbon stocks, thereby contributing to climate change mitigation. One should note, however, that land-use systems which maximize both carbon and profit are not realistic [18]. Smallholder farming systems should therefore be managed for profit, and opt for an acceptable rather than a maximum level of stored carbon. Additional mitigation benefits result from reduced deforestation and forest degradation as the need for wood fuel harvest diminishes by substituting wood fuels from forests with wood fuels from agriculture or agroforestry. Further benefits accrue when energy-intensive synthetic fertilizers are substituted for organic fertilizers (through biological nitrogen fixation and/or additional biomass).

In India, for example, an estimated 24,602 million trees outside forests supply 49% of the 201 million tons of fuelwood consumed by the country per year [19]. Integration of trees in cropping systems can provide significant financial benefits to the farmer, given the existence of a local fuelwood market [20]. The introduction of living fences in Central America has been shown to have a significantly positive impact on small farm incomes with an estimated internal rate of return of almost 30% [21]. In El Salvador, intercropping of eucalyptus trees with maize proved to be more profitable (20,558 Salvadoran Colones per hectare) than monocultures of either maize (12,013 Salvadoran Colones per hectare) or eucalyptus (17,807 Salvadoran Colones per hectare) [22].

The mitigation potential of agroforestry systems strongly depends on the type of system (agropastoral, silvopastoral, agrosilvopastoral) and the species used. Yet rough estimates indicate that agroforestry systems contain 50 to 75 Mg carbon per hectare, compared with row crops that contain less than 10 Mg carbon per hectare [18].

A further example is the pigeon pea IFES example in Malawi, an intercropping scheme between staple foods (mainly maize, sorghums, millets) and pigeon peas (*Cajanus cajan*), a nitrogen-fixing, multipurpose plant, which delivers protein-rich vegetables for human consumption, fodder for animals and woody plant material for cooking. One stem of local pigeon pea varieties can weigh over 800 g and – depending on the variety, the stove technology and the type of meal – one local plant can provide enough energy for a family of five to cook 1 to 2 meals per day for 3 to 8 months per year, thus reducing the need to collect fuelwood in the nearby forest reserve (Roth cited in [15]).

Similar results are reported from Asia. A study in Myanmar found on those farms that plant pigeon peas can satisfy more than 25% of their solid energy needs with pigeon pea stalks [23].

Other studies stress that such IFES can offer several co-benefits beyond food and energy alone. Under the term of Evergreen Agriculture, the World Agroforestry Centre (ICRAF) has been promoting intercropping maize with pigeon peas and other leguminous crops such as *Gliricidia sepium*, *Tephrosia candida* and *Faidherbia albia* as a source for additional biomass on the farm, particularly stressing their fertilizing effects on soils [24]. Garrity and colleagues report that several studies have shown after a 2-year to 3-year fallow that these plants provide 100 to 250 kg of nitrogen per hectare [24], enhancing the yields of the maize crops that follow and decreasing expenditures for synthetic fertilizers.

A study conducted by Ngwira and colleagues found that intercropping maize and pigeon pea under conservation agriculture presents a win–win scenario due to crop yield improvement and attractive economic returns provided future prices of maize and pigeon pea grain remain favorable [25]. Snapp and colleagues confirm this view, showing that grain yields from legume-intensified systems were comparable with yields from continuous sole maize [26]. They concluded that intercropping with leguminous crops can lead to more productive plots, yielding as much maize as sole monocultures plus an additional yield in fuelwood and pigeon pea grains.

The fact that diverse production systems and ecosystems produce more biomass than monocultures [27-29] means that opportunities for mitigation of climate change through carbon capture in biomass and soils can increase through such diversification. Furthermore, through the substitution of synthetic fertilizers with organic alternatives (such as leguminous crops), additional mitigation benefits accrue. A comprehensive study on the *Gliricidia* and maize intercropping system [30] measured the sequestered soil carbon and estimated carbon loss as soil carbon dioxide, which amounted to 67.4% of the sequestered soil carbon for the first 7 years in the intercropping system. This resulted in an annual net gain in soil carbon of 3.5 tons of carbon per hectare and year. The authors also included the potential for nitrous oxid**e** mitigation (as a result of no synthetic nitrogen fertilizer use), which was estimated to be 3.5 to 4.1 tons of carbon dioxide equivalent (CO_2e) per hectare and year, showing that reducing nitrous oxideemissions through including nitrogen-fixing species can significantly increase the overall mitigation benefit from the intercropping system. Yet the author also draws attention to the fact that, depending on the site characteristics, nitrous oxideemissions in the intercropping system can be higher than emissions from synthetic nitrogen fertilizers applied to a sole-maize site, negatively affecting the benefits of the intercropping system.

Additional mitigation benefits accrue when IFES are combined with energy-efficient end-use technologies such as improved cooking stoves. Each improved cooking stove, as such, can only contribute minimally to climate change mitigation. Yet considering the 2.5 billion current users of traditional biomass, the potential for GHG reductions is immense. The FAO estimates that between 125 and 459 megatons of carbon can be reduced globally per year through improved cooking stoves [31].

Viable bioenergy alternatives to fuelwood use

The integrated production of food crops, livestock, fish and bioenergy may lead to many synergies by adopting different agro-industrial technologies such as gasification or anaerobic digestion that allow maximum utilization of crops, livestock and their byproducts. These concepts have been described under several different names in the world; for example, the concept of circulative farming system or biomass town in Japan [32], the integrated three-in-one model in China [33] or the cascade systems in Germany [34].

At the simplest level, these systems involve the extraction of energy from agricultural residues, making use of freely available biomass. A good example is the installation of simple anaerobic digesters for biogas production in smallholder crop–livestock systems found throughout the world, especially prevalent in East and Southeast Asia [35]. For instance, the National Biogas Program in Vietnam supported by the Ministry of Agriculture and the Netherlands Development Organization (SNV), has implemented about 250,000 smallholder biogas digesters in existing crop–livestock systems in Nepal since 1992, and 124,000 in Vietnam since 2003 [36].

While the gas is usually used for cooking, and sometimes for lighting, replacing the need to purchase fuelwood or gas, the effluent of these digesters – bioslurry – can be used as a replacement for chemical fertilizers, such as urea. A study in Nicaragua found that the use of fuelwood can be reduced by 50% through the installation of a small-scale biogas digester [37]. In Nepal, an average household of 6 to 7 people saves 2 to 3 tons of fuelwood per year through the use of biogas, reducing GHG emissions by 5 tons of CO_2e [38].

A survey from Vietnam found that, in addition to GHG saving from replacing kerosene with biogas, an average household can reduce their fertilizer use by almost 50% through the application of bioslurry [39]. The study further estimated that a household using bioslurry to offset chemical fertilizer could reduce their GHG emissions by roughly 0.08 tons of CO_2e per year. At the national level, full utilization of bioslurry as a replacement for urea could result in significant emission reductions – to the amount of 3.14 megatons of CO_2e when comparing the nitrogen availability in bioslurry with the national nitrogen consumption through urea.

Yet despite all these benefits, the uptake of biogas technology has been relatively slow. The cost barrier for the initial investment and the often poor institutional support in terms of information, capacity-building and technical support are still significant constraints that need to be overcome in most countries.

Another hurdle to upscaling IFES is the fact that data which could clearly show the benefits (or disadvantages) of IFES are relatively scare. Some statistics for biogas systems are listed in Table 1. The table shows the carbon dioxide reduction potential from biogas production through fossil fuel substitution, manure management and synthetic fertilizer substitution as well as savings in other energy carriers such as kerosene, coal and straw and/or the responding cost values. While the values for single inventions are minimal, the combined impacts of many biogas units can be immense. Chinese statistics show that while one biogas unit only saves 5 tons of CO_2e per year, the current reduction of GHG emission amounts to 150 megatons from 30 million units [40]. Conservative estimations by the Global Methane Initiative show that global emissions from manure in 2010 were 244 megatons of CO_2e [41], which illustrates the large potential of biogas installations for climate change mitigation from better manure management alone.

Although mostly implemented for the sake of self-sufficiency, there are also innovative IFES approaches supported by the private sector on a large scale, such as the business model promoted by CleanStar Mozambique [43]. This venture supports smallholder farmers to implement agroforestry systems on their own land, providing basic inputs and technical assistance. Farmers benefit from increased food production for their own use and through the sale of surpluses to the company. CleanStar expects farmers to at least triple their cash incomes. A portion of one of the products, cassava, is further processed into ethanol-based cooking fuel, which is sold into the urban Maputo market, where the vast majority of people rely on increasingly expensive, deforestation-based charcoal from neighboring provinces. The company aims to involve 2,000 smallholders by 2014 over 5,000 hectares of land, supplying at least 20% of Maputo households with a clean alternative to charcoal and thus protecting 4,000 hectares of indigenous forests per year.

More complex and usually more resource-efficient systems at the farm level that integrate many different crops, animals and technologies are location specific, mostly very small scale, and are often unique cases run by dedicated individuals. These systems demonstrate the potential for but also highlight the need for skills and dedication. They can, however, inspire adoption of efficient and climate-smart practices and approaches and can pave the way towards gradual transformation to more resilient farming systems.

The Tosoly Farm in Santander in Colombia, for instance, is a highly integrated farm, aiming to produce food and energy for family consumption and for sale (Preston cited in [15]). The cropping is based on sugar cane, coffee and cocoa with multi-purpose trees and livestock. Most of the energy on the farm is produced by gasification of the sugar cane bagasse and the stems from mulberry forages (100 kWh/day). The 800 W installed capacity of photovoltaic panels are estimated to yield 8 kWh daily. Eight biodigesters produce 6 m^3 of biogas daily, two-thirds of which are converted to electricity (6 kWh/day). The remainder is employed for cooking. After deducting the electricity used to drive the

Table 1 Carbon dioxide equivalent emission reduction potential and cost and resource savings through smallholder biogas units

Type	CO_2e emission reductions (tons per year)			Savings		References
	Domestic energy replacement	Manure management	Synthetic fertilizer replacement	Domestic energy	Fertilizer replacement	
Household, Vietnam (1)	2.15	–	0.08	–	US$77.57/year	[39]
Household, Vietnam (2)	2.9	2.1	0.5	US$ 120/year	–	[41]
National potential, Vietnam	630 million	–	3.14 million	–	US$673.4 million/year	[39,42]
Household, Nepal	–	–	–	2 to 3 tons of wood/year	–	[38]
Household, China		5		US$ 5 (wood);US$ 158 (coal)/year		[40]
30 million units, China (2005)		150 million		2.2 million tons of coal; 2.1 million tons of wood; 5 million tons of straw/year	–	Liu (2008) cited in [40]
National potential, China	–	–	–	93 million tons of coal/year	–	[40]

CO_2e, carbon dioxide equivalent.

farm machinery and to supply the house, the potentially exportable surplus is 104 kWh daily, which at the current price of electricity (US$0.20/kWh) would yield an annual return of US$7,600 if sold to the grid under the same conditions[c].

Byproducts of the energy production are bioslurry from the biogas digester and biochar from the gasification process. Both byproducts are used to improve soil fertility on the farm, returning the nutrients that had been formerly extracted through biomass removal back to the fields. Assuming that most of the carbon in the biochar will be permanently sequestered when incorporated into the soil, Rodriguez calculated that from the 50 kg of bagasse dry matter derived daily from 330 kg/day of sugar cane stalks and 14 kg of dry matter from tree stems, the daily production of biochar from the Tosoly farm is about 6 kg (or 2.19 tons per year), resulting in an annual carbon sequestration of 1,460 kg (or 5.35 tons of carbon dioxide) [44].

Other renewable energies in rural farming systems

In many situations, the production of renewable energy can feasibly go well beyond bioenergy alone. Other locally available (nonbiological) renewables can be incorporated, such as solar thermal, photovoltaic, geothermal, wind and hydropower. Accelerating the substitution of fossil fuels with renewable energy sources can particularly enhance access to modern energy such as electricity, and can provide the lowest cost option for energy access in remote areas [45].

Technologies for small-scale renewable applications are mature and may often provide synergies with agricultural production. For example, small wind-driven pumps can provide water for irrigation to increase productivity. Wind turbines can provide electricity without competing for cropland: by sitting them in or around fields, they can harness the wind whilst the crops harness the solar energy, making double use of land.

Technological diversity combined with reasonable simplification can provide more reliable and more flexible solutions that allow IFES to also provide energy needs for modern communities; that is, electricity, heat and transport energy. Bioenergy combined with other renewables can provide greater reliability and diversity, as in the case of wind power or solar heating with biomass backup. Such hybrid systems are still relatively scarce, but have gained increasing popularity among researchers in developed countries and some emerging economies. For instance, Pérez-Navarro and colleagues evaluated an innovative system combining a biomass gasification power plant, a gas storage system and standby generators to stabilize a generic 40 MW wind park [46], showing that biomass could be a key factor to make wind energy a reliable commercial source of electricity.

Upscaling: scientific basis for policy support

Many traditional and indigenous smallholder farming systems have blended with modern agricultural science, and dozens of public and private projects have demonstrated evidence that IFES based on agro-ecological farming practices at different scales can contribute to climate-smart agriculture and food security [15]. However, evidence remains scattered and successful practices are often not upscaled due to the complexity of IFES. The more crops and processes involved, the greater the losses in economies of scale and the greater the skills required if a farmer is to be expected to manage such an array of crops and equipment.

Farmers therefore tend to prefer simple farming systems over more complex, integrated alternatives, as the workload and knowledge intensity is less, and the income generation potential is often higher in monoculture systems [12]. This is particularly true for large-scale , commercial agriculture, which depends almost exclusively on reduced labor and increased mechanization to reduce costs. Many experts are therefore convinced that efforts to modify current trends will require clear policy incentives if more diverse and integrated systems are to be upscaled considerably.

Productivity of farming systems would need to be measured as total agricultural output balanced against total farm inputs and externalities, rather than single-crop yield, to compare the efficiency of different farming systems in a holistic way. A study from Brazil found that a 10 to 20 hectare agroforestry-based home garden generated a net income comparable with 1,000 hectares of pasture cattle ranch, and presented multiple additional benefits such as rural employment for women and reduced deforestation [47]. In Indonesia, researchers found that diverse home gardens have higher standing biomass, produce a higher net income and improved stability, sustainability and equity than the cultivation of rice monoculture systems [48].

Policy interventions could help to compensate for lower yields, rewarding those systems that reduce externality costs and that generate nonmonetary benefits to the society as a whole, such as climate benefits, clean water or increased biodiversity. Interventions are also helpful to incentivize the quicker uptake of IFES, to make them easier to afford in the first place, especially for those types that involve energy technologies such as biogas digesters or improved cooking stoves. Policy could also help to address the knowledge intensity of IFES by providing adequate education, knowledge dissemination and technical support among rural communities.

Some argue that the best way to handle IFES is through division of labor in order to tackle both the knowledge intensity and the increased workload related to IFES, splitting responsibilities between different actors [15]. The farmer does what he does best – farming – and other local operators handle the energy part of IFES. In this case, adequate skills need to be provided to these local energy entrepreneurs. Several programs focusing on training these operators have been developed by organizations such as SNV, the United Nations Environment Program and the United Nations Foundation [49], or by countries such as China or Vietnam [35].

In China, for instance, the government supports local biogas service stations that sell and implement biogas digesters and end-use appliances and offer technical support and maintenance services, which they charge small fees for. The government makes sure that shopowners are regularly trained and updated, and it evaluates their quality of work. Currently, there are about 41,000 such service stations in place [35].

Other successful approaches include farmer field schools or farmer-to-farmer training. In the case of large, commercial enterprises, smallholders working in outgrower schemes are often trained by the company itself – as can be seen in the case of CleanStar Mozambique, for example.

Despite increasing evidence that diverse and integrated systems such as IFES have the large potential to contribute to climate-smart agriculture, it seems logical that decision-makers need a solid scientific basis that justifies and underpins policy support for their scaling up. It has been widely recognized that a reductionist approach based on single-sector oriented research methods has failed in analyzing adequately complex, multidisciplinary, large-scale global phenomena; the adequate approach should rather be holistic and integrated, based on a systems-oriented analysis [50]. Yet scientific interpretation, analysis and assessment of the dynamic, variable and site-specific interactions within integrated farming systems are still subject to debate [51] – a problem, given that such holistic assessments are crucial to generate the data needed to inform decision-making.

While studies or frameworks for assessing farming systems and related livelihoods do exist, they often focus on one sector alone. For instance, some of these studies focus on food production only, whereas others have a strong emphasis on bioenergy production. Some of the current bioenergy sustainability schemes, such as those recognized by the European Commission might lend themselves to initiate such an assessment – yet most of them are very strong on lifecycle analyses of GHG emissions while they are very weak on social sustainability aspects such as food security, as shown by two recent studies [52,53]. Such certification standards do not sufficiently account for food security and environmental impacts which should be equally considered with, if not prioritized over, GHG emissions to justify the denomination sustainable biofuels. Some experts therefore argue that current certification schemes such as those developed by the European Commission and other existing certification initiatives – for example, the Roundtable of Sustainable Soy, the Better Sugarcane Initiative and the Roundtable on Sustainable Palmoil – alone will not be sufficient to address food security and environmental concerns, and that additional appropriate policies are needed to mitigate social and environmental risks [54].

Of the few assessments that are explicitly designed for integrated systems, some are particularly strong on the biophysical side of integrated farming systems and eco-agricultural farming practices – for instance, analysis on the performance of prototype farms on the basis of 12 agro-ecological indicators and the framework for interpreting indicators of ecosystem services [54,55] – while others rather focus on the socioeconomic side, such as the analysis of small-scale bioenergy initiatives [56]; only few studies holistically address both biophysical and socioeconomic aspects of farming systems – for example, the indicator-based assessment of ecosystem change and human-well-being [57]. Comprehensive methodologies for integrated landscape assessments still need to be developed as recently discussed at the Nairobi International Conference for the Landscapes for People, Nature and Climate Initiative held in March 2012.

This complexity poses a large challenge to both scientists and policy-makers alike. While indicators for the assessment of integrated systems need to be comprehensive, it is crucial to keep the measurement of indicators as simple as possible. According to Malkina-Pykh [50], they need to be easily understandable and transparent; policy relevant; theoretically well founded (scientific basis); sensitive to (human-induced) changes; show changes in time; technically measurable (reproducible, reasonable costs, and so forth); and appropriate to scale (in time as well as geographically and/or spatially). Defining a comprehensive set of indicators with easily measurable and appropriate thresholds for sustainable agriculture is a challenge that has yet to be tackled. Simplifying a holistic assessment for the sake of policy-making will be crucial, yet it bears the risk of losing important details and weight.

Taking this knowledge into account, the FAO aims to build on existing methodologies for the development of a holistic, but also practical, way of informing policy regarding IFES. A recently developed tool to build on is the FAO's Operator Level Food Security Assessment Tool, which can be used to assess how an existing or planned agricultural operation with a bioenergy component may affect food security. The tool consists of three parts, each including a number of indicators, which address key environmental and socioeconomic aspects of agricultural operations that are directly linked to one or more dimensions of food security. For each indicator, specific thresholds and a scoring system are provided. Another helpful FAO tool, the EX-ACT (*Ex Ante* Appraisal Carbon-balance) Tool, provides *ex ante* estimations of the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration, indicating its effects on the carbon balance.

Conclusion

Increasing evidence shows that diverse and integrated farming systems and landscapes that are based on agro-ecological farming practices can present a robust pathway towards climate-smart agriculture, in times of a steadily growing world population and increasing resource competition. Yet, without the necessary institutional and policy adjustments, the way towards more climate-smart production systems will be long, if not impossible. In order to accelerate this process, and to facilitate policy decision-making, science and traditional knowledge need to be integrated to inform and engage all stakeholders alike. Key to this is a robust and practical, yet holistic, assessment of successful integrated farming systems and landscapes and their institutional and policy requirements based on system-oriented thinking.

As labor costs increase and less and less people live in rural areas to feed a growing and increasingly urban population, monoculture-based agriculture is steadily increasing. Yet the apparent growth in yields and efficiency require external, energy-intensive inputs and bring about high externality costs for both society and the environment. Agro-ecological farming systems and landscapes, on the other hand, are very knowledge intensive, and require capacity-building and strong institutional support. For that reason, an assessment methodology needs to be developed to demonstrate under which circumstances (how, where and when) the several additional benefits such as increased resilience to climate risks, resource efficiency and improved livelihoods make an investment in IFES worthwhile.

Beyond the management of single farms, good governance systems for landscape planning and management that advocate for a balanced approach between different land-use functions and nature conservation are crucial – an area that needs more attention in both science and policy discussions. Be it through payments for environmental services, or through innovative policy incentives and/or regulations, the multiple functions of land, water and biomass use require careful planning with active participation of the local population.

This being said, it is important to note that current land-use systems, including agriculture, will not be able to change overnight, yet require carefully designed and locally adapted solutions, tailored towards the needs of the population within different agro-ecological zones. The interlinkages between food and energy, two basic human needs, need to be carefully considered in future decision-making, in order to improve food security, on the one hand, and both climate change adaptation and mitigation on the other.

Endnotes

[a] Adaptive capacity is more than access to and availability of economic assets, yet there is currently 'little scholarship (and even less agreement) on criteria or variables by which adaptive capacity can be measured and by which the adaptive capacity of global regions can be quantitatively compared' ([58], p. 898). For the sake of

this publication, we therefore attempt to illustrate the economic gains through IFES in order to provide some basis to give some value to adaptive capacity.

[b] Note multiple-factor causation: deforestation is caused by combinations of multiple factors. According to a study by Geist and Lambin ([12], p. 146), at the global level, the most important direct driver for deforestation is agricultural expansion, which is associated with 96% of all deforestation cases they assessed. This includes both subsistence agriculture and commercial plantations for food, feed and biofuel production. Another primary driver of deforestation infrastructure is development for settlements and transport (72%) and wood extraction (67%), both commercial for trade (52%) and fuelwood for domestic use (28%) ([12], p. 146). Yet the weighting of these drivers varies widely between different countries, regions and continents [12], as can be seen in the case of fuelwood use in Africa, for instance. Percentages indicate the frequency of specific proximate causes in tropical deforestation based on the assessment of 152 cases. Multiple counts are possible.

[c] Mr Preston, the owner of the farm, decided not to produce more energy as the feed-in tariff offered to him was only one-tenth of what the electricity was sold for to the community.

Abbreviations

CO_2e: carbon dioxide equivalent; FAO: Food and Agriculture Organization of the United Nations; GHG: greenhouse gas; IFES: integrated food–energy systems..

Competing interests

The author declares that she has no competing interests.

Acknowledgements

The author thanks Olivier Dubois, Rainer Krell and Craig Jamieson who co-authored the FAO's overview report on IFES, in which the original concept of IFES was developed. The author also thanks the German Ministry of Agriculture and Consumer Protection (BMELV) for financing the FAO project on this topic. The author is grateful to colleagues Elizabeth Beall, Erika Felix and Marja Tapio Bistrom who gave valuable recommendations.

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Received: 2 April 2012 Accepted: 25 June 2012
Published: 16 July 2012

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doi:10.1186/2048-7010-1-9
Cite this article as: Bogdanski: **Integrated food–energy systems for climate-smart agriculture.** *Agriculture & Food Security* 2012 **1**:9.