Agricultural Systems 155 (2017) 136–146

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Review

Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty

R.D. Garrett[a],*, M.T. Niles[b,c], J.D.B. Gil[a,d], A. Gaudin[e], R. Chaplin-Kramer[f], A. Assmann[g], T.S. Assmann[h], K. Brewer[e], P.C. de Faccio Carvalho[i], O. Cortner[a], R. Dynes[j], K. Garbach[k], E. Kebreab[l], N. Mueller[m], C. Peterson[e], J.C. Reis[n], V. Snow[j], J. Valentim[o]

[a] Department of Earth and Environment, Boston University, 685 Commonwealth Avenue, Boston, MA 02215, USA
[b] Department of Nutrition and Food Sciences, University of Vermont, 350 Carrigan Wing, 109 Carrigan Drive, Burlington, VT 05405, USA
[c] Food Systems Program, University of Vermont, 350 Carrigan Wing, 109 Carrigan Drive, Burlington, VT 05405, USA
[d] Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands
[e] Department of Plant Sciences, University of California, Davis, 1 Shields Ave, Davis, CA 95616, USA
[f] Natural Capital Project, Stanford University, 371 Serra Mall, Stanford, CA 94305, USA
[g] Agricultural Institute of Paraná, Rod. BR 158, 5517 SR, CEP 85501-970, Pato Branco, PR, Brazil
[h] Departamento of Agronomy, Federal University of Technology-Paraná, Via do Conhecimento, Km 1, CEP 85503-390 Pato Branco, PR, Brazil
[i] Departamento de Plantas Forrageiras e Agrometeorologia, Universidade Federal do Rio Grande do Sul, Av Bento Gonçalves 7712, Porto Alegre, RS 91540-000, Brazil
[j] AgResearch, Lincoln, Private Bag 4749, Christchurch 8140, New Zealand
[k] Point Blue Conservation Science, 3820 Cypress Dr. #11, Petaluma, CA 94954, USA
[l] Department of Animal Science, University of California, Davis, CA 95616, USA
[m] Department of Earth System Science, University of California, Irvine, Croul Hall, Irvine, CA 92697, USA
[n] Embrapa Agrossilvopastoral, Sinop, MT, Brazil
[o] Agroforestry Research Center of Acre, Embrapa Acre, Rio Branco, AC CEP 70770-901, Brazil

ARTICLE INFO

Keywords:
Food systems
Agroecology
Sustainable agriculture
Mixed crop livestock
Ecosystem services

ABSTRACT

Crops and livestock play a synergistic role in global food production and farmer livelihoods. Increasingly, however, crops and livestock are produced in isolation, particularly in farms operating at the commercial scale. It has been suggested that re-integrating crop and livestock systems at the field and farm level could help reduce the pollution associated with modern agricultural production and increase yields. Despite this potential, there has been no systematic review to assess remaining knowledge gaps in both the social and ecological dimensions of integrated crop and livestock systems (ICLS), particularly within commercial agricultural systems. Based on a multi-disciplinary workshop of international experts and additional literature review, we assess the current knowledge and remaining uncertainties about large-scale, commercial ICLS and identify the source of remaining knowledge gaps to establish priorities for future research. We find that much is understood about nutrient flows, soil quality, crop performance, and animal weight gain in commercial ICLS, but there is little knowledge about its spatial extent, animal behavior or welfare in ICLS, or the tradeoffs between biodiversity, pest and disease control, greenhouse gas (GHG) mitigation, and drought and heat tolerance in ICLS. There is some evidence regarding the economic outcomes in commercial ICLS and supply chain and policy barriers to adoption, but little understanding of broader social outcomes or cultural factors influencing adoption. Many of these knowledge gaps arise from a basic lack of data at both the field and system scales, which undermines both statistical analysis and modeling efforts. Future priorities for the international community of researchers investigating the tradeoffs and scalability of ICLS include: methods standardization to better facilitate international collaborations and comparisons, continued social organization for better data utilization and collaboration, meta-analyses to answer key questions from existing data, the establishment of long term experiments and surveys in key regions, a portal for citizen science, and more engagement with ICLS farmers.

---

* Corresponding author.
E-mail address: rgarr@bu.edu (R.D. Garrett).

http://dx.doi.org/10.1016/j.agsy.2017.05.003
Received 17 December 2016; Received in revised form 2 May 2017; Accepted 8 May 2017

1. Introduction

The last century has brought remarkable transformation in global food systems via the proliferation of non-draught powered farm machinery, improvements in plant and animal genetics, the invention of synthetic fertilizers, and increased trade (Busch and Bain, 2004; Foley et al., 2011). While many of these changes have contributed to increasing global food production, another consequence has been the de-coupling of crop and livestock systems and a loss of agricultural diversity at both the field and territorial (regional) scales in many countries (Naylor et al., 2005). Although these two functional groups of agricultural production worked for hundreds of years in a synergistic capacity on rural landscapes throughout the world (FAO, 2010), crops and livestock are increasingly produced in isolation, separated in some cases by great distances (Peyraud et al., 2014), particularly in commercial-scale farms - farms that sell a majority of their production (Robinson et al., 2011). This de-coupling has engendered major changes in production practices and agricultural supply chains and numerous social and environmental externalities (Naylor et al., 2005). It has been suggested that re-integrating crop and livestock systems at the field or territorial level (by co-locating them in space and over time) (Bell and Moore, 2012) could help solve many of the social, economic, and environmental challenges that our global food system now faces (FAO, 2010; Martin et al., 2016; Wilkins, 2008). Some governments have even developed programs and policies to promote the re-integration of commercial scale crop and livestock systems in their countries (e.g. Australia's Grain and Graze program (http://lwa.gov.au/programs/grain-and-graze) and Brazil's National Crop-Livestock-Forestry Integration Policy (Law 12,805/13).

The integration of crop and livestock systems may occur in a variety of forms. Examples of field level integration of crop and livestock systems include: i) grazing livestock on crops, crop residues, or forage cover crops, ii) phase farming, i.e., rotating pastures and cropland over several years, and iii) grazing of understory vegetation in vineyards or orchards. Examples of territorial integration include: i) cooperative arrangements between different farms to allow temporary grazing on crop residue, ii) regional planning to match supply and demand for livestock feed, and iii) trading animal wastes and crop residues between farms (Martin et al., 2016).

Understanding the interactions between dynamic configurations of crops, forages, and livestock and the broader natural and human systems in which they are embedded requires models and data that span many disciplines and scales. Yet, research on social and ecological outcomes of different forms of ICLS, particularly within commercial farming systems (as opposed to subsistence farming systems), remains limited or regionally concentrated, minimizing the capacity to compare across systems and regions and advance a broader understanding about the cost and benefits of ICLS. Due to these research gaps it is hard to take stock of which questions we are currently able to answer with existing data and models, and where substantial capacity needs to be built to address present knowledge gaps and future questions.

For this reason, we convened a meeting of international scientists, practitioners, and modeling experts as part of a National Science Foundation “Science, Engineering, and Education for Sustainability” grant (#1415352). The meeting took place at the University of California, Davis in April, 2015 and was attended primarily by researchers from the two focal countries of the grant: Brazil and the United States, but also participants from other regions where commercial ICLS is also occurring at scale including New Zealand and Europe. During the two-day workshop, we addressed the following questions, which we detail in this paper:

i) What do we currently know about the social and ecological processes in commercial ICLS?
ii) What knowledge about these processes do we lack that prevents us from understanding the likely social and environmental outcomes if ICLS are adopted on a wide scale and the factors that may limit adoption?
iii) What is the source of these knowledge gaps?
iv) What data, models, and analysis should be prioritized to address these knowledge gaps and their sources?

Answers to these questions are necessary to help define priorities for the scientific community, funding agencies, and practitioners to advance ICLS research across multiple disciplines. They can also help set the agenda for more applied work and partnerships among farmers, researchers, and non-profit organizations and help design systems, management options and policies which will help disseminate ICLS across an array of potentially interested communities.

The following paper represents a systematic effort based on the aforementioned workshop and additional literature review to answer these questions, particularly as they pertain to large scale, commercial agricultural systems. To structure our findings, we identified four fields of inquiry relevant to ICLS. These fields of inquiry include:

i) Nutrient flows and crop performance in ICLS;
ii) Animal performance, health, and welfare in ICLS;
iii) Emergent ecosystem properties of ICLS; and
iv) Social benefits and barriers to ICLS adoption.

Based on this review and synthesis we summarize whether major knowledge gaps are due to data or model limitations, or both. We then discuss key priorities to advance research on ICLS in the future based on our analysis.

This work builds on the results of a global consultation on ICLS (FAO, 2010) and several other comprehensive reviews of current knowledge related to ICLS in commercial systems in Australia, Brazil, Europe, and the United States (Bell and Moore, 2012; Bonaudo et al., 2014; de Moraes et al., 2014a; Lemaire and Franzluebbers, 2013; Martin et al., 2016; Peyraud et al., 2014; Russelle et al., 2007; Sulc and Franzluebbers, 2014). Most of these reviews focus on the benefits of ICLS within a single geographic region, although some also touch on challenges for their adoption. We extend these reviews by synthesizing research on commercial ICLS between regions and including more information on the social aspects of ICLS. More importantly, we use this synthesis of current knowledge to highlight remaining knowledge gaps and identify future research priorities.

2. ICLS in the focal regions

This paper focuses on current knowledge of ICLS in Australia, Brazil, France, New Zealand, and the United States due to our interest in larger scale, commercial agricultural systems and the existence of sufficient prior research on ICLS in these regions. There are likely other countries (i.e. Canada) where commercial ICLS can be found, but there is little existing research from these regions (a major knowledge gap in and of itself).

Within the focal regions, ICLS systems take a variety of forms but typically involve cereals and sheep or beef cattle (Table 1). Large farms (> 20 ha) are the most common and dominate the landscape (except for Brazil where large farms comprise 40% of the farms but 95% of the area) (Adamopoulos and Restuccia, 2014; Lowder et al., 2016). In all regions, large scale monocultures and/or continuous pasture systems contribute greatly to the country's major environmental challenges, including greenhouse gas emissions, water and air pollution, salinization, and biodiversity loss (Lapola et al., 2013; Monaghan et al., 2007; Rengasamy, 2006; Stoate et al., 2001; Tilman et al., 2002).

Despite the commonality of large farm sizes, the focal regions span a range of social (policy, culture, and economic) and ecological (climate, topography, and vegetation) contexts (Garrett et al., 2017; Peyraud et al., 2014), which makes their comparison helpful for understanding how differing social and ecological contexts affect outcomes in com-

Table 1
Types of field scale, commercial ICLS present in studies included in this review by country. Estimates of ICLS abundance are obtained from national agricultural censuses (Eurostat, 2010; IBGE, 2006; Statistics New Zealand, 2012; USDA, 2012), except for Australia where data come from Bell and Moore (2012).

Country	Type of ICLS	Overall abundance	Example studies
Australia	Wheat, canola, and brassicas with sheep Chickpea and cereals with beef cattle	70% of crop farms; 30% of livestock products	● Bell and Moore, 2012 ● Bell et al., 2014 ● Dove et al., 2015 ● Rodriguez et al., 2014
Brazil	Soy, corn, and wheat cropping with beef cattle	13% of crop farms; 36% of crop area; 7% of livestock farms; 23% of pasture area	● de Faccio Carvalho et al., 2010 ● de Moraes et al., 2014b ● Gil et al., 2015 ● Salton et al., 2011
France	Cereals with beef cattle Rapeseed and sunflower with beef cattle Mixed arable with sheep	8% of farms	● Ryschawy et al., 2012 ● Veysset et al., 2014 ● Bonaudo et al., 2014
New Zealand	Wheat, brassicas, kale, fodder beet, oats, barley, peas, beans, turnips, and rapeseed with beef cattle, dairy cattle or sheep Wine grapes with sheep	44% of grain farms; 50% of grain area; 2% of livestock farms; 1% of livestock area	● Dynes et al., 2010 ● Niles et al., In review
United States	Vegetables with small and large livestock Legumes and forage crops with dairy cattle Cotton with beef cattle Fruit and nut orchards with small livestock	7% of crop farms; 1% of crop area	● Allen et al., 2007 ● Franzluebbers, 2007 ● Russelle et al., 2007 ● Sulc and Franzluebbers, 2014 ● Tracy and Zhang, 2008

mercial ICLS. In fact, objectives and rational for ICLS adoption greatly varies between the commercial systems considered here. A key objective of the integration of pasture and grazing into continuous, specialized cropping systems are to reduce fertilizer applications, GHG emissions, and water pollution (Franzluebbers, 2007; Russelle et al., 2007). Across all systems, an additional goal of ICLS is to help farmers reduce their reliance on costly external inputs, achieve greater self-sufficiency, and reduce risk to climate and market fluctuations (Bell and Moore, 2012; Bonaudo et al., 2014). For arid regions, objectives also include a reduction of total external water needs per unit of food produced (Allen et al., 2005). In contrast, in regions where extensive grazing is common, a major focus of integrating cropland into livestock systems is to help improve soil quality and pasture productivity to increase stocking rates and spare natural vegetation from further agricultural expansion (de Moraes et al., 2014a).

Census data and prior research suggest that commercial ICLS were once common across these regions, but are now quite rare (Garrett et al., 2017; Peyraud et al., 2014; Sulc and Franzluebbers, 2014), except for Australia and New Zealand. The low prevalence and diversity of ICLS within large scale commercial farming systems in the focal regions stands in stark contrast to their abundance within smaller scale, rainfed or dryland farming systems within Asia and Africa. As of 1996, “mixed” crop-livestock systems were estimated to provide over 50% of the world's meat and over 90% of its milk (Thornton and Herrero, 2001). Approximately 75–90% of the ruminant livestock present in South and Southeast Asia are located on integrated farms (Devendra and Thomas, 2002) and most of the dryland farming systems of Sub Saharan Africa integrate crops and livestock (Powell et al., 2004). An investigation of the social and ecological knowledge related to commercial ICLS can thus contribute to better understanding of why ICLS are so rare in high-income as compared to low-income country contexts and their potential benefits if adopted on a wide scale.

3. Nutrient flows and crop performance in ICLS

3.1. What do we know?

Shifts in soil health and pest incidence with livestock integration influence both crop and pasture productivity of ICLS. The direction of this relationship is highly dependent on climatic, biophysical, and co-management variables. For example, in Australia, Brazil, and Europe the incorporation of grasses and forages into cropland has been shown to increase yields in subsequent soybean, corn, and rice as well as livestock productivity (Bell et al., 2014; de Moraes et al., 2014a; Finn et al., 2013; Lunardi et al., 2008). In the United States grazing cattle on pasture and forages has had no impact on yields of subsequent corn or cotton crops, though it has helped reduce fertilizer and irrigation water needs (Allen et al., 2005; Sulc and Tracy, 2007). While the magnitude of these effects varies with biophysical conditions, including soil type, temperature and, precipitation patterns, and the photosynthetic efficiency of the grass species (Assmann et al., 2007; Costa et al., 2014; Drinkwater et al., 1998; Ma et al., 2003; Mazzoncini et al., 2011; Russell et al., 2006), livestock integration often increases total food yields per unit of applied N and P thanks to more productive use of residual soil nutrients (Martins et al., 2014; Sartor et al., 2011).

The integration of a grazed forage crop can also enhance soil organic carbon (SOC) which provides multiple co-benefits such as accumulation and retention of N and P and other ecosystem services, except when external fertilizer applications are excessive (Carvalho et al., 2010; Palmer et al., 2017). Land-based livestock integration enhances C-, N-, P-, and S-cycling (Acosta-Martínez et al., 2010; Archer and Smeins, 1991; Drinkwater et al., 1998; Soussana and Lemaire, 2014), but the impacts on carbon and nutrient accumulation remain strongly influenced by co-management factors such as N and P fertilization, tillage methods, rotation length and grazing intensity (de Faccio Carvalho et al., 2010; de Lima Wesp et al., 2016; Savian et al., 2014). SOC is usually highest under high N fertilization combined with no-till planting (Lal, 2004, 2011; Mazzoncini et al., 2011). Benefits of grazing can decline or even reverse at high stocking rates (de Faccio Carvalho et al., 2010; Drinkwater et al., 1998) when N and P levels become undesirably high and heterogeneous, resulting in potentially higher N and P runoff if fertilizer applications are not managed accordingly (Russelle et al., 2007; Snow et al., 2014). However, if carefully managed, integrated fertilization strategies which account for N and P credit from manure can help reduce losses (Rotz et al., 2009) and N addition on a grazed forage can eliminate the need for N applications on a subsequent grain crop while maintaining yields (Assmann et al., 2003; Sandini et al., 2011).

3.2. What don't we know?

Although extensive information is available in annual crop systems, little is known about the carbon and nutrient dynamics of livestock grazing in the understory of perennial orchards or vineyards (Russelle et al., 2007). In addition, there is very little information on K or S dynamics across all systems. Given how dependent these processes are to the specific context (what crops, climate, soils, rotation, and co-management practices), very little is understood about the generalizability of existing case studies and which factors are more important for determining outcomes. Additionally, there is a need for more information on the potential co-benefits of changes in carbon and nutrient cycles and improved biodiversity. Finally, progress in plant breeding for these systems have been extremely slow and little information is available about forage and crop target traits are most beneficial in ICLS.

4. Animal performance and related outcomes in ICLS

4.1. What do we know?

4.1.1. Meat and milk production

In regions with low natural soil fertility, pastures that are overgrazed and not amended with soil correctives (e.g. lime and fertilizers) and resown with desirable species become degraded quickly, often resulting in low animal productivity, land abandonment and combined with new deforestation to source more fertile soils (Balbino et al., 2011; Walker et al., 2000). In these places ICLS can serve an important role in livestock intensification by contributing to enhanced soil fertility and pasture productivity thereby improving forage quantity and quality and animal nutrition and by reducing direct costs of pasture reclamation (Domiciano et al., 2016). Among existing studies in Australia, Brazil, and the United States there is strong evidence that sheep and beef cattle meat production per unit of land (assessed via changes in daily animal weight gain) is at least equal to, if not substantially higher in ICLS than in pure pasture systems (de Moraes et al., 2014b; Dove et al., 2015; Faria, 2016; Sulc and Franzluebbers, 2014). However, with the exception of an intensification strategy based on biological nitrogen fixation by legumes (Valentim and Andrade, 2005), initiatives are dependent on high N fertilizer inputs to improve pasture productivity (Assmann et al., 2010). Grazing intensity is a key factor influencing outcomes in both continuous pasture systems and ICLS (de Lima Wesp et al., 2016; Kunrath et al., 2014). Moderate grazing intensities tend to result in the best outcomes; low intensity grazing can result in an underutilization of pasture productivity, while at higher grazing intensities individual animal performance can be reduced (de Faccio Carvalho et al., 2007).

By increasing pasture productivity, ICLS has the potential to increase stocking rates and reduce time to slaughter, resulting in higher land use efficiency and potentially sparing land for other uses or forest (Oltjen and Beckett, 1996). For example, in Brazil, stocking rates can be increased from 1 head/ha in extensive pastures to at least 2 head/ha in ICLS (Bonaudo et al., 2014) and the life cycle of grazed cattle can be reduced from an average of 36 months (Millen et al., 2011) to as low as 16 months (de Lima Wesp et al., 2016).

4.1.2. Resource efficiency

ICLS has less impact on productivity where pastures are already well managed (Hill et al., 2003; Janovick et al., 2003; Moore et al., 2009; Veysset et al., 2014). In these regions a more important benefit of ICLS practices is higher weight gain or milk production per unit cost and nutrient emissions (through lower use of feeds and feed concentrates). For example, in the northeast United States, replacing concentrate feeding with grazing in an integrated crop and dairy system has been shown to maintain milk production while reducing P soil accumulation and increasing profits (Rotz et al., 2002).

4.2. What don't we know?

Despite the findings presented above, previous studies have concluded that animal performance is under-represented relative to crop performance in ICLS studies (de Moraes et al., 2014b; Sulc and Franzluebbers, 2014). Most existing studies in the focal regions focus on ruminants, namely sheep and cattle, due to their enhanced benefits (carbon and nutrient cycling, weed suppression, etc.) via grazing and their greater overall prevalence (versus other forms of ruminants, such as buffaloes and goats). There is very little information on the outcomes associated with integration of monogastrics (birds or swine) in cropping systems in the focal regions, as is more common in highly diversified organic or biodynamic farming systems.

There is almost no literature on ICLS using a mixture (rather than a single species) of livestock in a synergistic capacity. There is also little understanding of animal behavior, genetics, reproduction, welfare or meat quality (de Moraes et al., 2014b). Existing evidence on animal welfare comes mainly from the silvopasture literature and is inferred from grazing behavior and productivity gains. In silvopasture, animal welfare may be improved through less exposure to stressful microclimatic conditions and less time spent grazing (Karki and Goodman, 2010; Paciullo et al., 2008). Additional knowledge gaps include the survival of pathogens in animal manure in ICLS systems and subsequent infection or transmission to other individuals within the herd or potential implications for food safety. A recent study showed that pathogens in manure can survive for considerable amount of time under open-air conditions (Biswas et al., 2016).

5. Emergent ecosystem properties of ICLS

5.1. What do we know?

5.1.1. Biodiversity

The incorporation of a pasture phase in a crop rotation cycle can have dramatic effects on the abundance and composition of aboveground and soil communities. ICLS tend to have a higher fungal: bacterial ratio than continuous cropping systems, in addition to greater microbial biomass (Acosta-Martínez et al., 2010) and more stable microbial communities (Lacombe et al., 2009). However, increases in total microbial biomass and cycling enzyme activity depend on grazing intensity and tillage practices (Patra et al., 2005). ICLS using moderate grazing intensities tend to have higher microbial diversity compared to other management systems (Chávez et al., 2011; Moraes et al., 2014) but lower than perennial pastures (Borges et al., 2009). Abundance and diversity of soil macrofauna also increases under ICLS, especially under no-till (Marchão et al., 2009). Shifts in microbial biomass and composition can be an important driver of soil C and C input (Sankaran and Augustine, 2004). Mixtures of row crops, pastures, and trees within farm landscapes increases habitat for local wildlife (Karlen et al., 1994; Russelle et al., 2007; Wilkins, 2008), β-biodiversity, that is, the degree of heterogeneity in species compositions between landscape patches (Verdade et al., 2014) and ecosystem services, such as pollination and predation on agricultural pests (Bretagnolle et al., 2011; Tscharntke et al., 2005).

5.1.2. Pest and disease control

Biological control can increase or decrease within more diversified farming systems (Chaplin-Kramer et al., 2011), since non-crop elements in the landscape may harbor pests and diseases along with beneficial species (Purcell and Saunders, 1999). Nevertheless, several studies have found that the integration of perennial forages and grazing into annual croplands has reduced disease and weed abundance in annual crops, thereby reducing biocide applications and the need for tillage (Harvey and McNevin, 1990; Johnson et al., 1999; Russelle et al., 2007). Diversifying landscapes, through introduction of cover crop and sod-based crop rotations, has also been shown to reduce pressure from insect and nematode pests through a combination of increased predatory insect habitat (Tillman et al., 2004) and disruption of pest lifecycles (Hartzog and Balkcom, 2003). It is generally agreed that monocropping requires significantly more fertilizer and biocide applications compared to more diverse, integrated systems that include a rotation of the land under different plant species (Martinelli et al., 2010; Pimentel, 2005; Smil, 1999; Tilman et al., 2001).

5.1.3. GHG mitigation

Substituting animal manure for synthetic fertilizers decreases CH_4 and N_2O emissions in ICLS (Salton et al., 2014; Zanatta and Salton, 2010). However, the use of no-till amplifies the GHG mitigation benefits of ICLS, particularly in tropical regions, by reducing soil oxidation and organic material decomposition (Baker et al., 2007; Mangalassery et al., 2015; Sulc and Franzluebbers, 2014; Wanniarachchi et al., 1999).

As an alternative to continuous livestock production, ICLS can also result in lower GHGs per unit of food and land via faster weight gain and higher stocking rates. When compared to intensive cattle farms, lower GHGs are due to lower reliance on imported feeds, which have numerous GHGs embedded in them (via fertilizer and fuel use) and require substantial energy to transport (Adler et al., 2015). In addition, manure produced in intensive cattle farms is usually stored in a lagoon that contributes to greater methane emissions if not covered (Montes et al., 2013).

5.1.4. Drought and heat tolerance of crops

The structural and biological complexity of ICLS is assumed to promote greater resistance to stress events and faster recovery speed after stress. Stress events include climatic aberrations such as heat waves and drought (Shennan, 2008), as well as extreme events such as hurricanes and floods. For soy production, ICLS have been shown to experience smaller productivity losses than non-integrated systems during low-rainfall years (Salton et al., 2014). However, soy-corn rotations faced with recurrent drought years have produced mixed results, with the effect of tillage (no-till versus conventional tillage) often being more important than livestock integration to mitigate yield losses (Franzluebbers and Stuedemann, 2014) and under high grazing intensity, ICLS may negatively affect soil moisture (Martins et al., 2016). The majority of evidence in support of ICLS contributions to increased climate resilience come from the positive effects on related variables such as soil organic matter content (Tracy and Zhang, 2008) and associated biogeochemical buffering (Murphy, 2015), soil structure (Salton et al., 2008), microbial abundance (Acosta-Martínez et al., 2010), and improved water and nutrient retention (Allen et al., 2007; Bell et al., 2014; Haan et al., 2006), rather than direct crop yield responses to climate stress.

5.2. What don't we know?

The potential of ICLS to reduce nutrient leaching compared to very high intensity livestock systems remains to be quantified and few studies compare the pollution implications of ICLS versus confinement systems. Similarly, there is a great deal of interest, but little data on sediment loads in ICLS under different rotational schemes. In general, higher animal stocking rates are expected to result in higher erosion (Briske et al., 2011).

Despite the potential for GHG reduction from ICLS, few life cycle data are available to evaluate this potential systematically across production systems. GHG impacts will be highly dependent on the level of intensification in ICLS and the degree of spatial and system integration (Lemaire and Franzluebbers, 2013). N_2O emissions from manure are also uncertain and the conditions for partial denitrification and methods to facilitate complete denitrification to atmospheric N require further study. With respect to resilience there is some evidence of enhanced crop resistance and recovery to climate stresses, but there is less information on whether ICLS are more resistant to pest and disease stresses.

Overall, there is very little understanding of the trade-offs between different ecosystem services discussed above across different types of ICLS or between ICLS and continuous production systems (Garbach et al., 2016). This is a limitation of the existing agroecology literature more generally, as most studies focus on only one or two (often correlated) ecosystems services. As such, there is little information to inform multi-criteria policy decisions or understand differential impacts on different stakeholders.

6. Social benefits and barriers to ICLS adoption

6.1. What do we know?

6.1.1. Economic costs and benefits

The economic benefits of ICLS are even more context dependent than the ecological outcomes because they depend simultaneously on the markets, technologies, and policies in a given region that influence production costs and output prices, as well as the biophysical and climate factors that influence pasture productivity and meat and milk production. The relative economic benefits of ICLS at the field level also depend on the system to which they are being compared, whether or not farmers are able to achieve economies of scope vis-à-vis more specialized systems, and the existence of other integration opportunities at the territorial scale (Martin et al., 2016; Veysset et al., 2014).

In comparison to extensive, continuous rainfed beef cattle production (e.g. Southeast Australia, Brazil), ICLS with both pasture and oilseeds and grains can result in substantially higher profitability (Dove et al., 2015; Katsvairo and Cox, 2000; Lunardi et al., 2008). In some places they can also be more profitable than continuous cropping (de Oliveira et al., 2013; Ryschawy et al., 2012), but these results depend on the costs of external inputs and labor costs. Where (and when) fertilizers are very costly and labor costs are very low, integrated systems will be more attractive than systems that rely heavily on external inputs (all intensively managed specialized systems) or mechanization (specialized cropping systems in particular) (Janovick et al., 2003). Additionally, if the full social costs of fertilizers are internalized via policies taxing carbon or nitrogen, or if nitrogen emissions are heavily regulated, then ICLS will also be more attractive (Garrett et al., 2017). In places where seasonal feed scarcities result in high feed costs (e.g. Australia), ICLS will have substantially lower costs than specialized livestock operations (Bell et al., 2014).

6.1.2. Risk mitigation and resilience

A more generalizable observation about ICLS is that these systems can provide a more stable and diversified source of income throughout the year versus continuous crop or livestock production, which helps farmers reduce their risk to all types of shocks (Bell et al., 2014; Franzluebbers et al., 2011; Ryschawy et al., 2012; Sanderson et al., 2013). When producers have both livestock and crops already present on their farm they can more easily adjust levels of each system increasing their resilience to major changes in prices or weather, rather than trying to bring entirely new sets of crop or animal systems into production (Bell and Moore, 2012; Dynes et al., 2010). These benefits appear particularly strong among small farmers where the income smoothing and reduced weather risks associated with ICLS have disproportionately large impacts on household resilience (Ryschawy et al., 2012; Thornton and Herrero, 2014). However the impacts of diversification on income resilience may actually be higher in larger farms (Abson et al., 2013; Bell and Moore, 2012).

6.1.3. Barriers and incentives

ICLS tend to require greater managerial intensity, knowledge and capital (to invest in both crop and livestock infrastructure) than continuous crop or pasture systems (Bell and Moore, 2012; Niles et al., In review). The use of rotations requires extensive planning and potential reductions in short-term output in favor of longer-term resilience (Gil et al., 2016). A pasture-crop rotation that requires cattle to be moved frequently may require more labor, or more skilled labor, than an extensive system with no pasture rotations or a completely mechanized monoculture. Husbandry of livestock year-round involves leisure tradeoffs in comparison to seasonal crop production. ICLS, by virtue of including both crops and livestock, requires a greater diversity of supply chain infrastructure and higher upfront costs than continuous cropping or livestock. Adequate processing facilities, marketing channels, and transportation routes for both systems must be present (Gil et al., 2016; Moraine et al., 2014). ICLS adoption also requires a supportive policy environment. Where environmental policies regulating carbon and nitrogen emissions are strong, climate insurance is lacking, tariffs on imported feeds are high, and food safety policies do not prohibit the presence of animals in cropland areas, ICLS will likely be more abundant (Garrett et al., 2017).

Culture is an important factor influencing preferences related to ICLS and access to information about ICLS. In particular, farmers' traditions of using continuous production systems and norms of valuing single crop yields rather than farm-level performance inhibit their use of ICLS (Sulc and Tracy, 2007). Social prestige associated with different forms of agriculture and historical experiences with cropping versus livestock systems are also important motivators of behavior (Gil et al., 2016).

6.2. *What don't we know?*

Very little is known about the landscape level economic resilience benefits of adopting either field level or territorial forms of ICLS, though several recent studies have begun to tackle this important subject (Martin et al., 2016; Moraine, Duru, et al., 2017; Poccard-Chapuis et al., 2014). In terms of the net social benefits of integrated systems, to date there has been no comprehensive calculation of the total economic value to society of the changes in GHG emissions, water quality, and water usage that emerge from ICLS vis-à-vis continuous cropping or pasture. Such accounting is necessary to evaluate whether or not these systems result in higher net social benefits and should be encouraged through policy incentives.

Of key importance, yet poorly understood, is the role of knowledge systems and social networks in influencing farmers' access to information and perceptions about the costs and benefits of ICLS versus continuous crop or pasture, or their agricultural preferences and attitudes related to ICLS. Agricultural research and extension agencies, civil society groups, and farmer-to-farmer knowledge transfers can all influence the adoption of best management and sustainable practices (Breetz et al., 2005; Lubell et al., 2014; Prokopy et al., 2008; Risgaard et al., 2007). Yet it remains unclear what types of knowledge are more critical for ICLS adoption and what vehicles for knowledge transfer are most effective for behavior change: formalized scientific knowledge from extension agents, traditional knowledge from neighbors and friends, or other sources. The adoption of ICLS may be particularly sensitive to the configuration of agricultural knowledge systems, since these systems are often organized around single commodities. Additional knowledge gaps around ICLS uptake include the role of gender, farm succession, and cooperation (see Fig. 1).

7. Common sources of knowledge gaps across all fields

7.1. *Lack of long-term, ecosystem-scale experiments and animal infrastructure*

Although long-term studies assessing agronomic and biogeochemical outcomes in ICLS exist within certain regions, data characterizing the outcomes of commercial ICLS remains sparse in many parts of the focal regions. Long-term datasets are particularly valuable in understanding co-benefits of shifts in soil C, such as changes in soil structure and nutrient availability, which may take years to detect following changes in tillage or cropping systems (Giller et al., 2009). System scale experiments and monitoring equipment will be necessary to collect data on emergent aspects of ICLS such as net GHG, N runoff, biodiversity, long-term herd dynamics, and animal welfare.

One factor limiting data acquisition on animals in ICLS in particular is that many cropping experiment stations lack adequate infrastructure and staffing to support animal management and shelter. Consequently, animals are sometimes rented for the purposes of including a grazing cycle in ICLS experiments. The result of this is a much greater focus on the cropping aspects of the experimental program than the animal performance and welfare. Such systems are also weak with respect to considering the long-term management, performance and welfare of both individual animals and the herd.

7.2. *Inadequate modeling capacity*

Due to the scarcity of experimental systems and the absence of GHG or N-cycle monitoring at system scales in most of the regions of the world, scientific analysis must rely heavily on models to examine potential outcomes. Many existing publicly-accessible models of commercial ICLS fail to capture the full suite of synergies between crop and livestock systems leading to emergent outcomes. Known examples include the IFSM, used primarily in the United States (Rotz et al., 2005), APSIM (Holzworth et al., 2014) and OVERSEER (Wheeler et al., 2003, 2006), used primarily in New Zealand, and FSSIM, used primarily in Europe (Louhichi et al., 2010) but even these models fail to capture all the factors identified as important above. For livestock in particular, most modelers ignore the heterogeneous nutrient return associated with grazing (see the review by Snow et al., 2014), while others approach the issue by coupling specific models (McGechan and Topp, 2004; Romera et al., 2017). These coupled models are complex, cumbersome to use, limited in applicability and may fail to fully capture the nutrient feedbacks within the system in terms of soil and nutrient processes. New methods that incorporate additional feedbacks between crops and livestock components, while remaining pragmatic with respect to model complexity are needed. Recently, Snow et al. (2017) documented such a method for grazed crops, and approaches such as these might be incorporated into more models to capture the important aspects of nutrient cycling in ICLS. Applying existing models to study ICLS performance under climate change is particularly problematic since empirical evidence is lacking as to the effect of crop-livestock integration on climate resilience.

7.3. *Few comparable socioeconomic datasets*

Isolated datasets of household socio-economic conditions, the economics of monoculture systems, and the economics of certain complex smallholder systems have been developed, yet very few large datasets have been collected specifically to examine the economies of scope that may be present in commercial ICLS. We have no global dataset of national ICLS adoption rates, let alone more spatially explicit adoption rates. Most agricultural censuses do not fully capture this information. Previous efforts to estimate “mixed” crop and livestock systems by countries and ecoregions, e.g. Robinson et al. (2011) focus on low-income countries and are not very precise for understanding field level integration. They estimate the prevalence of mixed systems using a combination of remotely sensed cropland and rangeland data, growing season information, and population density. Spatially explicit information on the global extent of ICLS is necessary to better understand the environmental impacts of current agricultural practices globally, their potential resilience to changes in climate, as well as the social and ecological factors are associated with higher or lower uptake across regions.

7.4. *Conceptual and methodological difficulties in linking ICLS research between scales*

Amidst the continued challenges of analyzing the social benefits of ICLS at the field or farm scale, there is additional difficulty in trying to integrate crop and livestock systems beyond the farm (Moraine et al., 2016). Not only do the relevant metrics of analysis sometimes differ between scales, but also the methods by which these metrics are

Summary: Existing knowledge and knowledge gaps about commercial ICLS

What we know: ICLS can enhance soil organic carbon (SOC) accumulation and the availability of N and P in soils. It can also reduce N and P loss in soils. ICLS does not always increase yields in absolute terms, but it often increases yields per unit of N or P input. Nutrient and crop performance outcomes are dependent on biophysical context, and to an even greater degree, co-management factors. The use of ICLS can improve meat and milk production per unit of land in regions where pastures are poorly managed and per unit cost in regions where feed inputs are seasonally scarce. Outcomes are highly dependent on grazing intensity. Biomass and diversity of soil microbes and macrofauna tend to be higher and disease and weed abundance tend to be lower in ICLS versus continuous cropping systems. ICLS often have lower GHG emissions per unit of land compared to continuous cropping systems and lower GHG emissions per unit of food in comparison to continuous grazing or animal confinement systems. In certain contexts, ICLS provide higher profits than continuous pasture and continuous crop systems, but more generally they provide increased self-sufficiency and resilience to market and climate shocks. Farmers perceive numerous non-monetary benefits and challenges associated with ICLS that may support or offset the monetary benefits associated with these systems. As substantially more complex systems than continuous systems, ICLS have higher up-front costs and require a more diverse set of knowledge and supply chain infrastructure and a supportive policy environment.

What we don't know: Nutrient flows and crop performance are less well known in integrated tree-crop-livestock systems and there is little understanding of how contextual factors influence the generalizability of existing case studies. Little is known about monogastrics in ICLS or animal behavior, genetics, reproduction, and health in ICLS among all animal types. It remains unclear how species diversity in ICLS compares to continuous cropping or pasture systems or how nutrient emissions and sediment loads compare to high intensity livestock systems. Knowledge on the net GHG and nutrient emissions per unit of food produced is limited and tradeoffs between different ecosystem services in ICLS are rarely analyzed. Understanding of farmers' perceptions of ICLS, the landscape or regional impacts of ICLS if adopted on a wide scale, and the market and climatic conditions under which ICLS will have the highest levels of economic benefits versus continuous systems remains limited.

Fig. 1. A summary of current knowledge and knowledge gaps about commercial ICLS.

assessed varies (Poccard-Chapuis et al., 2014). Farm level outcomes and objectives can be assessed through household interviews, while community level outcomes and possibilities rely on participatory and focus group research with high community involvement. At both scales the development of ICLS knowledge is also challenged by a lack of farmer engagement to better understand the type of information farmers need to support their decision to utilize or not utilize ICLS.

7.5. Broader challenges

The development of the necessary experiments, surveys, and modeling tools needed to assess commercial ICLS is inhibited by compartmentalized thinking and case-specific research objectives across different research units. Across existing commercial scale ICLS experiments within the focal regions there is a lack of similarity between the specific crops and livestock examined as well as the underlying climatic, economic, and policy contexts, which impedes rigorous comparative analysis. Even more poignantly, there can be stark differences in the spatial scale (field versus territory) and temporal domains of interest (co-location within a year, i.e., intercropping versus co-location over multiple years i.e., rotations) within each research unit. Despite these differences, great potential exists to standardize methodologies across the many disciplinary and spatial components of ICLS research. It will continue to be difficult to link crop and animal models if we lack a common modeling protocol or if social and ecological scales cannot be aggregated to comparable scales. Finally, collaborations for ICLS research can be inhibited by intellectual property rules that limit data and model sharing. The publication of anonymized or aggregate open access datasets may help to overcome this limitation, as can efforts to synthesize existing research.

8. Priorities to advance ICLS research

Much progress has been made in understanding the individual components of ICLS and beginning to assess the complexities and feedbacks among their functional, ecological and social components, particularly at the field and farm level. However, major knowledge gaps remain about the implications of ICLS within the broader social and ecological systems in which they are embedded. Further work is now necessary to establish and continue scientific research in this area, as well as to advance collaboration on data collection and model development across continents.

First, it will be necessary to establish **common survey and sampling protocol** for ICLS indicators in future data collection efforts, such as agricultural censuses, so that data can be aggregated and compared between regions (for example in FAOStat – www.fao.org/faostat/). Agricultural censuses should include questions about the use of various types of ICLS on farms, accompanied by clear definitions about what is meant by ICLS. To avoid confusion, provide an additional layer of certainty, and aid aggregation efforts across regions, censuses should also ask about the specific practices underpinning ICLS (e.g. grazing animals on crop residues, grazing animals in the orchard understory, rotating crop and pasture areas, etc.). In a similar vein, comparability between experimental stations would be greatly enhanced by developing **common measurement protocols** and experiments of a similar organization and duration.

Research units across countries should establish **common modeling protocols** that will better enable coupling of crop and livestock systems. Protocols exist for managing data relevant to cropping systems such as the ICASA standard (White et al., 2013), but these do not include provision for data related to livestock and are also focused on the plot or field scale. These formats have not kept pace with recent innovations in model software, particularly with respect to cloud-based delivery of data, and the standards have limited reach into to wider ecosystem of modeling efforts worldwide (Holzworth et al., 2015). There seems to be renewed activity in data standards (e.g. (Ginaldi et al., 2016; Romero et al., 2012)) and interoperability (Antle et al., 2016) and some of these efforts include consideration of the data needs with respect to crop-livestock interactions. To facilitate coupling of crop and livestock models data on a similar time-scale, e.g., daily, are needed. Similarly, the output and input requirements of these models need to match.

In understanding the barriers and opportunities for the wide-scale adoption of ICLS it would be useful to establish **common protocols for focus group, survey and scenario building** exercises with farmers, stakeholders, and policy makers. If emerging efforts in Europe to analyze territorial scale impacts of ICLS are replicated in other regions (Moraine, Melac, et al., 2017; Ryschawy et al., 2017), there would be increased opportunities for generating generalizable knowledge about how landscape level transformation in agricultural systems could be achieved, a subject that is of broad interest to the sustainable agriculture community. In regions with a longer history of ICLS research and technology transfer, interviews, focus groups and surveys should be undertaken with practitioners to help codify existing knowledge and lessons learned. In some contexts, it would be helpful to partner with NGOs, businesses, and extension organizations that already work with farmers to monitor the effects of best practices and to create new portals for citizen science, whereby farmers can self-report their management practices.

In addition to a common protocol for collecting data, a clearinghouse should be established where relevant data that has already been collected can be accessed and utilized. Examples from related research areas include the International Forestry Resources Institute database and the United States Department of Agriculture Life Cycle Inventory database. The establishment of such a clearinghouse in combination with more standardized protocols for surveying and modeling would support much-needed meta-analyses to assess generalizable outcomes. To support all of these efforts an ongoing working group and scientific steering committee should be established to meet periodically to identify current state of knowledge and missing links. This effort can build on the three past international conferences on integrated crop, livestock, and forestry, which were held in Brazil (2007, 2012, and 2015).

9. Conclusions

A growing body of research suggests that re-integrating crop and livestock production at the field level may provide benefits for overcoming social and ecological challenges facing an increasingly globalized food system. However, to fully assess the potential benefits and costs of commercial ICLS systems across multiple farm types, scales, and environments of complex socioecological systems, additional research is needed. Baseline empirical data is especially critical to increase the sophistication and multidisciplinarity of modeling efforts that may help span these geospatial data limitations. Although further study is needed, there is already enough evidence for action, and it is essential to monitor and approach this with adaptive management in mind.

Here we have outlined the existing knowledge and knowledge gaps related to the social and ecological elements of ICLS, along with the sources of our knowledge gaps, to demonstrate the research, data and coordination efforts necessary to advance our understanding of ICLS. There are significant challenges involved in acquiring new sources of data to help address these gaps, particularly given historical limitations in funding for diverse, complex systems that require long-term research. In addition, the need for comparable data across many locations and conditions may be further limited by funding structures that seek to promote national systems and agendas.

While these are large obstacles to overcome, our efforts must be expanded and accelerated towards coordinating an international network of ICLS researchers working towards achieving some of the goals identified here, particularly related to the establishment of common protocols and opportunities for sharing data. Additionally, this international ICLS network would enable comparisons across different benchmark sites with different socioecological systems.

By synthesizing current research and knowledge gaps on ICLS and prioritizing the needs for future action, we hope that this work can lead to greater understanding and coordination among researchers and stakeholders, advancing the science and, where relevant, implementation of ICLS to address key social and ecological challenges. It is only through adequate data and unified research efforts that we can diagnose the drivers of impact within a system, and consequently understand how, why, and under what conditions ICLS can provide benefits over current agricultural systems.

Contribution statement

R. D. Garrett and M.T. Niles designed the study. All authors participated in the workshop that served as the basis for the study and/or helped to draft and edit the manuscript.

Acknowledgements

The authors thank Alan Franzluebbers for his helpful comments on the manuscript, Tom Tomich and Steve Vosti for their participation in the workshop that served as the basis for the study, and Nora O'Neil for helping to organize the workshop. This work was funded by the National Science Foundation [grant number 1415352] and further supported by Italy's Ministry for Environment, Land, and Sea and the Sustainability Science Program at Harvard University where three of the authors were Giorgio Ruffolo Fellows.

References

Abson, D.J., Fraser, E.D., Benton, T.G., 2013. Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture. Agric. Food Secur. 2, 2. http://dx.doi.org/10.1186/2048-7010-2-2.

Acosta-Martínez, V., Bell, C.W., Morris, B.E.L., Zak, J., Allen, V.G., 2010. Long-term soil microbial community and enzyme activity responses to an integrated cropping-livestock system in a semi-arid region. Agric. Ecosyst. Environ. 137, 231–240. http://dx.doi.org/10.1016/j.agee.2010.02.008.

Adamopoulos, T., Restuccia, D., 2014. The size distribution of farms and international productivity differences. Am. Econ. Rev. 104, 1667–1697.

Adler, A.A., Doole, G.J., Romera, A.J., Beukes, P.C., 2015. Managing greenhouse gas emissions in two major dairy regions of New Zealand: a system-level evaluation. Agric. Syst. 135, 1–9.

Allen, V.G., Baker, M.T., Segarra, E., Brown, C.P., Kellison, R., Green, P., Zilverberg, C.J., Johnson, P., Weinheimer, J., Wheeler, T., Segarra, E., Acosta-Martinez, V., Zobeck, T.M., Conkwright, J.C., Baker, M.T., Segarra, E., Brown, C.P., 2007. Integrated irrigated crop–livestock systems in dry climates. Agron. J. 99, 346–360.

Allen, V.G., Brown, C.P., Kellison, R., Segarra, E., Wheeler, T., Dotray, P.A., Conkwright, J.C., Grenn, C.J., Acosta-Martinez, V., 2005. Integrating cotton and beef production to reduce water withdrawal from the Ogallala aquifer in the southern High Plains. Agron. J. 97. http://dx.doi.org/10.2134/agronj2005.0556.

Antle, J.M., Basso, B., Conant, R.T., Godfray, H.C.J., Jones, J.W., Herrero, M., Howitt, R.E., Keating, B.A., Munoz-Carpena, R., Rosenzweig, C., et al., 2016. Towards a new generation of agricultural system data, models and knowledge products: design and improvement. Agric. Syst.

Archer, S., Smeins, F.E., 1991. Ecosystem-level processes. In: Grazing Manag. Ecol. Perspect. Timber Press Portland OR, pp. 109–139.

Assmann, T., Moraes, A., Assmann, A.L., Koehler, H.S., Sandini, I., 2003. Rendimento de milho em área de integração lavoura-pecuária sob o sistema de plantio direto, em presença e ausência de trevo branco, pastejo e nitrogênio. Rev. Bras. Ciênc. Solo 4.

Assmann, T.S., Assmann, A.L., Assmann, J.M., Soares, A., Bortolli, M., 2010. Produção de gado de corte e de pastagem de aveia em sistema de integração lavoura-pecuária em presença e ausência de trevo e nitrogênio. Rev. Bras. Zootec. 39, 1387–1397.

Assmann, T.S., Assmann, A.L., Soares, A.B., Cassol, L.C., Giasson, M.S., Giasson, N.F., 2007. Fixação biológica de nitrogênio por plantas de trevo (*Trifolium* spp.) em sistema de integração lavoura-pecuária no Sul do Brasil. Rev. Bras. Zootec. 36, 1435–1442.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—what do we really know? Agric. Ecosyst. Environ. 118, 1–5.

Balbino, L.C., Cordeiro, L.A.M., Porfírio-da-Silva, V., Moraes, A., Martínez, G.B., Alvarenga, R.C., Kichel, A.N., Fontaneli, R.S., Santos, H.P., Franchini, J.C., Galerani, P.R., 2011. Evolução tecnológica e arranjos produtivos de sistemas de integração lavoura-pecuária-floresta no Brasil [Evolution of technology and productive arrangements in integrated crop-livestock-forestry systems in Brazil]. Pesqui. Agropecuária Bras. 46. http://dx.doi.org/10.1590/S0100-204X2011001000001.

Bell, L.W., Moore, A.D., 2012. Integrated crop–livestock systems in Australian agriculture: trends, drivers and implications. Agric. Syst. 111, 1–12.

Bell, L.W., Moore, A.D., Kirkegaard, J.A., 2014. Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. Eur. J. Agron. 57, 10–20.

Biswas, S., Niu, M., Appuhamy, J., Leytem, A.B., Dungan, R.S., Kebreab, E., Pandey, P., 2016. Impacts of dietary forage and crude protein levels on the shedding of *Escherichia coli* 0157:H7 and Listeria in dairy cattle feces. Livest. Sci.

Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop-livestock systems. Eur. J. Agron. 57, 43–51. http://dx.doi.org/10.1016/j.eja.2013.09.010.

Borges, C.D., Mercante, F.M., Silva, R.F., Salton, J.C., 2009. Impacto de sistemas agropecuários na qualidade do solo. (O Solo E Produção Bioenergia Perspect. E Desafios).

Breetz, H.L., Fisher-Vanden, K., Jacobs, H., Schary, C., 2005. Trust and communication: mechanisms for increasing farmers' participation in water quality trading. Land Econ. 81, 170–190.

Bretagnolle, V., Gauffre, B., Meiss, H., Badenhausser, I., 2011. The role of grassland areas within arable cropping systems for the conservation of biodiversity at the regional level. In: Grassland Productivity and Ecosystem Services. CAB International, Wallingford, England, pp. 251–260.

Briske, D.D., Derner, J.D., Milchunas, D.G., Tate, K.W., 2011. An evidence-based assessment of prescribed grazing practices. In: Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. USDA-NRCS, Washington, DC, USA, pp. 21–74.

Busch, L., Bain, C., 2004. New! Improved? The transformation of the global agrifood system. Rural. Sociol. 69, 321–346.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Tillage Res. 110, 175–186.

Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J., Kremen, C., 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. Ecol. Lett. 14, 922–932.

Chávez, L.F., Escobar, L.F., Anghinoni, I., de Faccio Carvalho, P.C., Meurer, E.J., 2011. Diversidade metabólica e atividade microbiana no solo em sistema de integração lavoura-pecuária sob intensidades de pastejo. Pesqui. Agropecu. Bras. 46, 1254–1261. http://dx.doi.org/10.1590/S0100-204X2011001000020.

Costa, S.E.V.G.A., Souza, E.D., Anghinoni, I., Carvalho, P.C.F., Martins, A.P., Kunrath, T.R., Cecagno, D., Balerini, F., 2014. Impact of an integrated no-till crop-livestock system on phosphorus distribution, availability and stock. Agric. Ecosyst. Environ. 190, 43–51. http://dx.doi.org/10.1016/j.agee.2013.12.001.

de Faccio Carvalho, P.C., Anghinoni, I., de Moraes, A., de Souza, E.D., Sulc, R.M., Lang, C.R., Flores, J.P.C., Lopes, M.L.T., da Silva, J.L.S., Conte, O., Faccio Carvalho, P.C., Moraes, A., Souza, E.D., Terra Lopes, M.L., Silva, J.L.S., Lima Wesp, C., Levien, R., Fontaneli, R.S., Bayer, C., de Carvalho, P.C.F., da Conte, J.L.S.S., Lang, O., Reisdorfer, Claudete, Flores, J.P.C., 2010. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. Nutr. Cycl. Agroecosyst. 88, 259–273. http://dx.doi.org/10.1007/s10705-010-9360-x.

de Faccio Carvalho, P.C., Silva, J.L.S., Moraes, A., Fontanelli, R.S., Macari, S., Bremm, C., Trindade, J.K., 2007. Manejo de animais em pastejo em sistemas de integração lavoura-pecuária. In: International Symposium on Integrated Livestock Systems. UFPR, Curitiba.

de Lima Wesp, C., de Faccio Carvalho, P.C., Conte, O., Cadenazzi, M., Anghinoni, I., Bremm, C., 2016. Steers production in integrated crop-livestock systems: pasture management under different sward heights. Rev. Ciênc. Agronômica 47, 187–194.

de Moraes, A., de Faccio Carvalho, P.C., Anghinoni, I., Lustosa, S.B.C., Costa, S.E.V.G.D.A., Kunrath, T.R., 2014a. Integrated crop-livestock systems in the Brazilian subtropics. Eur. J. Agron. 57, 4–9. http://dx.doi.org/10.1016/j.eja.2013.10.004.

de Moraes, A., de Faccio Carvalho, P.C., Campos Lustosa, S.B., Lang, C.R., Deiss, L., 2014b. Research on Integrated Crop-livestock Systems in Brazil. 5. pp. 1024–1031.

de Oliveira, C.A., Bremm, C., Anghinoni, I., Moraes, A., Kunrath, T.R., de Faccio Carvalho, P.C., 2013. Comparison of an integrated crop–livestock system with soybean only: economic and production responses in southern Brazil. Renew. Agric. Food Syst. 28, 1–9. http://dx.doi.org/10.1017/S1742170513000410.

Devendra, C., Thomas, D., 2002. Crop–animal interactions in mixed farming systems in Asia. Agric. Syst. 71, 27–40.

Domiciano, L.F., Mombach, M.A., Carvalho, P., da Silva, N.M.F., Pereira, D.H., Cabral, L.S., Lopes, L.B., Pedreira, B.C., 2016. Performance and behaviour of Nellore steers on integrated systems. Anim. Prod. Sci.

Dove, H., Kirkegaard, J.A., Kelman, W.M., Sprague, S.J., McDonald, S.E., Graham, J.M., 2015. Integrating dual-purpose wheat and canola into high-rainfall livestock systems in south-eastern Australia. 2. Pasture and livestock production. Crop Pasture Sci. 66, 377–389. http://dx.doi.org/10.1071/CP14201.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–265.

Dynes, R., Burggraaf, V.T., Goulter, C.G., Dalley, D.E., 2010. Canterbury farming: production, processing and farming systems. Proc. N. Z. Grassl. Assoc. 72, 1–8.

Eurostat, 2010. European Union (EU) 2009/2010 Agricultural Census. European Comission.

FAO, 2010. An International Consultation on Integrated Crop-livestock Systems for Development: The Way Forward for Sustainable Production. Food and Agriculture Organization.

Faria, G., 2016. ILPF aumenta cinco vezes a produção de carne em Mato Grosso [WWW Document]. URL. https://www.embrapa.br/busca-de-noticias/-/noticia/17003406/ilpf-aumenta-em-cinco-vezes-a-producao-de-carne-em-mato-grosso.

Finn, J.A., Kirwan, L., Connolly, J., Sebastià, M.T., Helgadottir, A., Baadshaug, O.H., Bélanger, G., Black, A., Brophy, C., Collins, R.P., et al., 2013. Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment. J. Appl. Ecol. 50, 365–375.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., et al., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Franzluebbers, A.J., 2007. Integrated crop–livestock systems in the Southeastern USA. Agron. J. 99, 361. http://dx.doi.org/10.2134/agronj2006.0076.

Franzluebbers, A.J., Stuedemann, J.A., 2014. Crop and cattle production responses to tillage and cover crop management in an integrated crop–livestock system in the southeastern USA. Eur. J. Agron. 57, 62–70.

Franzluebbers, A.J., Sulc, R.M., Russelle, M.P., 2011. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Opportunities and Challenges for Integrating North-American Crop and Livestock Systems. Grassland Productivity and Ecosystem Services, Cambridge.

Garbach, K., Milder, J.C., DeClerck, F.A.J., de Wit, M.M., Driscoll, L., Gemmill-Herren, B., 2016. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agric. Sustain. 0, 1–22. http://dx.doi.org/10.1080/14735903.2016.1174810.

Garrett, R., Niles, M., Gil, J.D.B., Dy, P., Reis, J., Valentim, J.F., 2017. Policies for reintegrating crop and livestock systems: a comparative analysis. Sustainability 9, 473.

Gil, J., Siebold, M., Berger, T., 2015. Adoption and development of integrated crop–livestock–forestry systems in Mato Grosso, Brazil. Agric. Ecosyst. Environ. 199, 394–406.

Gil, J.D.B., Garrett, R.D., Berger, T., 2016. Determinants of crop-livestock integration in Brazil: evidence from the household and regional levels. Land Use Policy 59, 557–568.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res. 114, 23–34. http://dx.doi.org/10.1016/j.fcr.2009.06.017.

Ginaldi, F., Bindi, M., Dalla Marta, A., Ferrise, R., Orlandini, S., Danuso, F., 2016. Interoperability of agronomic long term experiment databases and crop model intercomparison: the Italian experience. Eur. J. Agron. 77, 209–222.

Haan, M.M., Russell, J.R., Powers, W.J., Kovar, J.L., Benning, J.L., 2006. Grazing management effects on sediment and phosphorus in surface runoff. Rangel. Ecol. Manag. 59, 607–615.

Hartzog, D.L., Balkcom, K., 2003. Initiation of the tri-state sodbased rotation project, an overview. In: Proc. Sod-Based Cropping Syst. Conf., Quincy, FL, pp. 20–21.

Harvey, R.G., McNevin, G., 1990. Combining cultural practices and herbicides to control wild-proso millet (*Panicum miliaceum*). Weed Technol. 433–439.

Hill, G.M., Hubbard, R.K., Lacy, R.C., Blalock, C., 2003. Integration of Winter Grazing and Irrigated Cotton Production. (Athens).

Holzworth, D.P., Huth, N.I., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., et al., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350.

Holzworth, D.P., Snow, V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W., Thorburn, P., 2015. Agricultural production systems modelling and software: current status and future prospects. Environ. Model. Softw. http://dx.doi.org/10.1016/j.envsoft.2014.12.013.

IBGE, 2006. Agriculture and Livestock Census. Instituto Brasileiro de Geografia e Estatística.

Janovick, N.A., Russell, J.R., Strohbehn, D.R., Morrical, D.G., Barnhart, S.K., Maxwell, D., Secor, L.J., 2003. Integration of Year-round Forage Management Systems for Spring-calving and Fall-calving Beef Cows (A Progress Report).

Johnson, A.W., Minton, N.A., Brenneman, T.B., Burton, G.W., Culbreath, A.K., Gascho, G.J., Baker, S.H., 1999. Bahiagrass, corn, cotton rotations, and pesticides for managing nematodes, diseases, and insects on peanut. J. Nematol. 31, 191.

Karki, U., Goodman, M.S., 2010. Cattle distribution and behavior in southern-pine silvopasture versus open-pasture. Agrofor. Syst. 78, 159–168. http://dx.doi.org/10.1007/s10457-009-9250-x.

Karlen, D., Varvel, G., Bullock, D., Cruse, R., 1994. Crop rotations for the 21st century. Adv. Agron. 53, 1–45.

Katsvairo, T.T.W., Cox, W.J.W., 2000. Economics of cropping systems featuring different rotations, tillage, and management. Agron. J. 92, 485–493.

Kunrath, T.R., Cadenazzi, M., Brambilla, D.M., Anghinoni, I., de Moraes, A., Barro, R.S., de Carvalho, P.C.F., 2014. Management targets for continuously stocked mixed oat × annual ryegrass pasture in a no-till integrated crop–livestock system. Eur. J. Agron. 57, 71–76. http://dx.doi.org/10.1016/j.eja.2013.09.013.

Lacombe, S., Bradley, R.L., Hamel, C., Beaulieu, C., 2009. Do tree-based intercropping systems increase the diversity and stability of soil microbial communities? Agric. Ecosyst. Environ. 131, 25–31.

Lal, R., 2011. Sequestering carbon in soils of agro-ecosystems. Food Policy 36, S33–S39.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22.

Lapola, D.M., Martinelli, L.A., Peres, C.A., Ometto, J.P.H.B., Ferreira, M.E., Nobre, C.A., Aguiar, A.P.D., Bustamante, M.M.C., Cardoso, M.F., Costa, M.H., Joly, C.A., Leite, C.C., Moutinho, P., Sampaio, G., Strassburg, B.N., Vieira, I.C.G., 2013. Pervasive transition of the Brazilian land-use system. Nat. Clim. Chang. 4, 27–35. http://dx.doi.org/10.1038/nclimate2056.

Lemaire, G., Franzluebbers, A., 2013. Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. http://dx.doi.org/10.1016/j.agee.2013.08.009.

Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Lansink, A.O., Van Ittersum, M., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agric. Syst. 103, 585–597.

Lowder, S.K., Skoet, J., Raney, T., 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev. 87, 16–29. http://dx.doi.org/10.1016/j.worlddev.2015.10.041.

Lubell, M., Niles, M., Hoffman, M., 2014. Extension 3.0: managing agricultural knowledge systems in the network age. Soc. Nat. Resour. 27, 1089–1103.

Lunardi, R., de Faccio Carvalho, P.C., Trien, C., Costa, J.A., 2008. Rendimento de soja em sistema de integração lavoura-pecuária: efeito de métodos e intensidades de pastejo “Soybean yield in an animal-crop rotation system: effects of grazing methods and intensities.”. Ciênc. Rural 38, 795–801.

Ma, B.L., Ying, J., Dwyer, L.M., Gregorich, E.G., Morrison, M.J., 2003. Crop rotation and soil N amendment effects on maize production in eastern Canada. Can. J. Soil Sci. 83, 483–495.

Mangalassery, S., Sjögersten, S., Sparkes, D.L., Mooney, S.J., 2015. Examining the potential for climate change mitigation from zero tillage. J. Agric. Sci. 153, 1151–1173.

Marchão, R.L., Lavelle, P., Celini, L., Balbino, L.C., Vilela, L., 2009. Soil macrofauna under integrated crop livestock systems in a Brazilian Cerrado Ferralsol. Pesqui. Agropecuária Bras. 44, 1011–1020.

Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M., Therond, O., 2016. Crop–livestock integration beyond the farm level: a review. Agron. Sustain. Dev. 36, 53.

Martinelli, L.A., Naylor, R., Vitousek, P.M., Moutinho, P., 2010. Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future. Curr. Opin. Environ. Sustain. 2, 431–438. http://dx.doi.org/10.1016/j.cosust.2010.09.008.

Martins, A.P., de Andrade Costa, S.E.V.G., Anghinoni, I., Kunrath, T.R., Balerini, F., Cecagno, D., Carvalho, P.C.D.F., 2014. Soil acidification and basic cation use efficiency in an integrated no-till crop-livestock system under different grazing intensities. Agric. Ecosyst. Environ. 195, 18–28. http://dx.doi.org/10.1016/j.agee.2014.05.012.

Martins, A.P., de Andrade Costa, S.E.V.G., Anghinoni, I., Kunrath, T.R., Cecagno, D., Reichert, J.M., Balerini, F., Dillenburg, L.R., de Carvalho, P.C.F., Martins, A.P., de Costa, S.E.V.G.A., Anghinoni, I., Kunrath, T.R., Cecagno, D., Reichert, J.M., Balerini, F., Dillenburg, L.R., de Carvalho, P.C.F., 2016. Soil moisture and soybean physiology affected by drought in an integrated crop-livestock system. Pesqui. Agropecuária Bras. 51, 978–989. http://dx.doi.org/10.1590/S0100-204X2016000800010.

Mazzoncini, M., Sapkota, T.B., Barberi, P., Antichi, D., Risaliti, R., 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Tillage Res. 114, 165–174.

McGechan, M.B., Topp, C.F.E., 2004. Modelling environmental impacts of deposition of excreted nitrogen by grazing dairy cows. Agric. Ecosyst. Environ. 103, 149–164.

Millen, D.D., Pacheco, R.D.L., Meyer, P.M., Rodrigues, P.H.M.P., De Beni Arrigoni, M., Arrigoni, M.D.B., 2011. Current outlook and future perspectives of beef production in Brazil. Anim. Front. 1, 46–52. http://dx.doi.org/10.2527/af.2011-0017.

Monaghan, R.M., Wilcock, R.J., Smith, L.C., Tikkisetty, B., Thorrold, B.S., Costall, D., 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. Agric. Ecosyst. Environ. 118, 211–222.

Montes, F., Meinen, R., et al., 2013. Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. J. Anim. Sci. 91, 5070–5094. http://dx.doi.org/10.2527/jas.2013-6584.

Moore, A.D., Bell, L.W., Revell, D.K., 2009. Feed gaps in mixed-farming systems: insights from the Grain & Graze program. Anim. Prod. Sci. 49, 736–748.

Moraes, A.D.E., Carvalho, P.C.D.F., Anghinoni, I., Lustosa, S.B.C., Costa, S.E.V.G.D.A., Kunrath, T.R., 2014. Integrated crop–livestock systems in the Brazilian subtropics. Eur. J. Agron. 57, 4–9. http://dx.doi.org/10.1016/j.eja.2013.10.004.

Moraine, M., Duru, M., Nicholas, P., Leterme, P., Therond, O., 2014. Farming system design for innovative crop-livestock integration in Europe. Animal 8, 1204–1217.

Moraine, M., Duru, M., Therond, O., 2017. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. Renewable Agric. Food Syst. 32, 43–56.

Moraine, M., Grimaldi, J., Murgue, C., Duru, M., Therond, O., 2016. Co-design and assessment of cropping systems for developing crop-livestock integration at the territory level. Agric. Syst. 147, 87–97.

Moraine, M., Melac, P., Ryschawy, J., Duru, M., Therond, O., 2017. A participatory method for the design and integrated assessment of crop-livestock systems in farmers' groups. Ecol. Indic. 72, 340–351.

Murphy, B.W., 2015. Impact of soil organic matter on soil properties - a review with emphasis on Australian soils. Soil Res. 53, 605–635. http://dx.doi.org/10.1071/SR14246.

Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Alder, J., Mooney, H., 2005. Losing the links between livestock and land. Science 310, 1621. http://dx.doi.org/10.1126/science.1117856.

Niles, M., Garrett, R., Walsh, D., 2017. Ecological and economic benefits and challenges for integrating sheep into viticulture production. Agron. Sustain. Dev (In review).

Oltjen, J.W.W., Beckett, J.L.L., 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74, 1406–1409.

Paciullo, D.S.C., Gomide, C.A.M., de Castro, C.R.T., Fernandes, P.B., Müller, M.D., de Pires, M.F.Á., Fernandes, E.N., Xavier, E.D.F., 2008. Caracteristicas produtivas e nutricionais do pasta em sistema agrossilvipastoril, conforme a distancia das arvores. pp. 1176–1183.

Palmer, J., Thorburn, P.J., Biggs, J., Dominati, E., Probert, M.E., Huth, N.I., Dodd, M., Snow, V., Larsen, J.R., Parton, W.J., 2017. Nitrogen cycling from increased soil organic carbon contributes both positively and negatively to ecosystem services in wheat agro-ecosystems. Front. Plant Sci. 8 (731). http://dx.doi.org/10.3389/fpls.2017.00731.

Patra, A.K., Abbadie, L., Clays-Josserand, A., Degrange, V., Grayston, S.J., Loiseau, P., Louault, F., Mahmood, S., Nazaret, S., Philippot, L., et al., 2005. Effects of grazing on microbial functional groups involved in soil N dynamics. Ecol. Monogr. 75, 65–80.

Peyraud, J.-L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: a review. Eur. J. Agron. 57, 31–42. http://dx.doi.org/10.1016/j.eja.2014.02.005.

Pimentel, D., 2005. Environmental and economic costs of the application of pesticides primarily in the United States. Environ. Dev. Sustain. 7, 229–252.

Poccard-Chapuis, R., Navegantes Alves, L., Grise, M.M., Bâ, A., Coulibaly, D., Ferreira, L.A., Lecomte, P., 2014. Landscape characterization of integrated crop–livestock systems in three case studies of the tropics. Renewable Agric. Food Syst. 29, 1–12. http://dx.doi.org/10.1017/S174217051400009X.

Powell, J.M., Pearson, R.A., Hiernaux, P.H., 2004. Crop–livestock interactions in the West African drylands. Agron. J. 96, 469–483.

Prokopy, L.S., Floress, K., Klotthor-Weinkauf, D., Baumgart-Getz, A., 2008. Determinants of agricultural best management practice adoption: evidence from the literature. J. Soil Water Conserv. 63, 300–311.

Purcell, A.H., Saunders, S.R., 1999. Fate of Pierce's disease strains of Xylella fastidiosa in common riparian plants in California. Plant Dis. 83, 825–830.

Rengasamy, P., 2006. World salinization with emphasis on Australia. J. Exp. Bot. 57, 1017–1023.

Risgaard, M.-L., Frederiksen, P., Kaltoft, P., 2007. Socio-cultural processes behind the differential distribution of organic farming in Denmark: a case study. Agric. Hum. Values 24, 445–459.

Robinson, T.P., Thornton, P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A.M.O., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., 2011. Global Livestock Production Systems. FAO and ILRI.

Rodriguez, D., Cox, H., Power, B., et al., 2014. A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric. Syst. 126, 50–61.

Romera, A.J., Cichota, R., Beukes, P.C., Gregorini, P., Snow, V.O., Vogeler, I., 2017. Combining restricted grazing and nitrification inhibitors to reduce nitrogen leaching on New Zealand dairy farms. J. Environ. Qual. 46, 72–79.

Romero, C.C., Hoogenboom, G., Baigorria, G.A., Koo, J., Gijsman, A.J., Wood, S., 2012. Reanalysis of a global soil database for crop and environmental modeling. Environ. Model. Softw. 35, 163–170.

Rotz, C.A., Sharpley, A.N., Satter, L.D., Gburek, W.J., Sanderson, M.A., 2002. Production and feeding strategies for phosphorus management on dairy farms. J. Dairy Sci. 85, 3142–3153.

Rotz, C.A., Soder, K.J., Howard Skinner, R., Dell, C.J., Kleinman, P.J., Schmidt, J.P., Bryant, R.B., 2009. Grazing can reduce the environmental impact of dairy production systems. Forage Grazinglands 7 (0–0). http://dx.doi.org/10.1094/FG-2009-0916-01-RS.

Rotz, C.A., Taube, F., Russelle, M.P., Oenema, J., Sanderson, M.A., Wachendorf, M., 2005. Whole-farm perspectives of nutrient flows in grassland agriculture. Crop Sci. 45, 2139–2159.

Russell, A.E., Laird, D.A., Mallarino, A.P., 2006. Nitrogen fertilization and cropping system impacts on soil quality in Midwestern Mollisols. Soil Sci. Soc. Am. J. 70, 249–255.

Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering integrated crop–livestock Systems in North America. Agron. J. 99, 325. http://dx.doi.org/10.2134/agronj2006.0139.

Ryschawy, J., Choisis, N., Choisis, J.P., Joannon, A., Gibon, A., 2012. Mixed crop-livestock systems: an economic and environmental-friendly way of farming? Animal 6, 1722–1730. http://dx.doi.org/10.1017/S1751731112000675.

Ryschawy, J., Martin, G., Moraine, M., Duru, M., Therond, O., 2017. Designing crop–livestock integration at different levels: toward new agroecological models? Nutr. Cycl. Agroecosyst. 1–16.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: toward a sustainable production system. Agric. Ecosyst. Environ. 190, 70–79.

Salton, J.C., Mielniczuk, J., Bayer, C., Boeni, M., Conceição, P.C., Fabrício, A.C., Macedo, M.C.M., Broch, D.L., 2008. Soil aggregation and aggregate stability under crop-pasture systems in Mato Grosso do Sul State, Brazil. Rev. Bras. Ciênc. Solo 32, 11–21.

Salton, J.C., Mielniczuk, J., Bayer, C., Fabrício, A.C., Macedo, M.C.M., Broch, D.L., 2011. Contents and dynamics of soil carbon in integrated crop-livestock systems. Pesqui. Agropecu. Bras. 46, 1349–1356. http://dx.doi.org/10.1590/S0100-204X2011001000031.

Sanderson, M.a., Archer, D., Hendrickson, J., Kronberg, S., Liebig, M., Nichols, K., Schmer, M., Tanaka, D., Aguilar, J., 2013. Diversification and ecosystem services for conservation agriculture: outcomes from pastures and integrated crop–livestock systems. Renewable Agric. Food Syst. 28, 129–144. http://dx.doi.org/10.1017/S1742170512000312.

Sandini, I.E., de Moraes, A., Pelissari, A., Neumann, M., Falbo, M.K., Novakowiski, J.H., 2011. Efeito residual do nitrogênio na cultura do milho no sistema de produção integração lavoura-pecuária. Ciênc. Rural 41.

Sankaran, M., Augustine, D.J., 2004. Large herbivores suppress decomposer abundance in a semiarid grazing ecosystem. Ecology 85, 1052–1061.

Sartor, L.R., Assmann, T.S., Soares, A.B., Adami, P.F., Assmann, A.L., Pitta, C.S.R., 2011. Nitrogen fertilizer use efficiency, recovery and leaching of an Alexander grass pasture. Rev. Bras. Ciênc. Solo 35, 899–906.

Savian, J.V., Neto, A.B., de David, D.B., Bremm, C., Schons, R.M.T., Genro, T.C.M., do Amaral, G.A., Gere, J., McManus, C.M., Bayer, C., de Faccio Carvalho, P.C., 2014. Grazing intensity and stocking methods on animal production and methane emission by grazing sheep: implications for integrated crop-livestock system. Agric. Ecosyst. Environ. 190, 112–119. http://dx.doi.org/10.1016/j.agee.2014.02.008.

Shennan, C., 2008. Biotic interactions, ecological knowledge and agriculture. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 363, 717–739. http://dx.doi.org/10.1098/rstb.2007.2180.

Smil, V., 1999. Nitrogen in crop production: an account of global flows. Glob. Biogeochem. Cycles 13, 647–662.

Snow, V.O., Cichota, R., McAuliffe, R., Hutchings, N.J., Vejlin, J., 2017. Increasing the spatial scale of process-based land use models by representing heterogeneity: the case of urine patches in grazed pastures. Environ. Model. Softw. 90, 89–106.

Snow, V.O., Rotz, C.A., Moore, A.D., Martin-Clouaire, R., Johnson, I.R., Hutchings, N.J., Eckard, R.J., 2014. The challenges–and some solutions–to process-based modelling of grazed agricultural systems. Environ. Model. Softw. 62, 420–436.

Soussana, J.-F., Lemaire, G., 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. Agric. Ecosyst. Environ. 190, 9–17.

Statistics New Zealand, 2012. 2012 Agricultural Census Tables.

Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., De Snoo, G.R., Eden, P., 2001. Ecological impacts of arable intensification in Europe. J. Environ. Manag. 63, 337–365.

Sulc, R.M., Franzluebbers, A.J., 2014. Exploring integrated crop–livestock systems in different ecoregions of the United States. Eur. J. Agron. 57, 21–30. http://dx.doi.org/10.1016/j.eja.2013.10.007.

Sulc, R.M., Tracy, B.F., 2007. Integrated crop–livestock systems in the U.S. corn belt. Agron. J. 99, 335–345.

Thornton, P.K., Herrero, M., 2014. Climate change adaptation in mixed crop-livestock systems in developing countries. Glob. Food Secur. 3, 99–107. http://dx.doi.org/10.1016/j.gfs.2014.02.002.

Thornton, P.K., Herrero, M., 2001. Integrated crop–livestock simulation models for scenario analysis and impact assessment. Agric. Syst. 70, 581–602. http://dx.doi.org/10.1016/S0308-521X(01)00060-9.

Tillman, G., Schomberg, H., Phatak, S., Mullinix, B., Lachnicht, S., Timper, P., Olson, D., 2004. Influence of cover crops on insect pests and predators in conservation tillage cotton. J. Econ. Entomol. 97, 1217–1232.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. http://dx.doi.org/10.1038/nature01014.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., Dobson, Andrew, Howarth, R., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284. http://dx.doi.org/10.1126/science.1057544.

Tracy, B.F., Zhang, Y., 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics with an integrated crop-livestock system in Illinois. Crop Sci. 48, 1211–1218. http://dx.doi.org/10.2135/cropsci2007.07.0390.

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. Ecol. Lett. 8, 857–874.

USDA, 2012. Agricultural Census. United States Department of Agriculture.

Valentim, J.F., Andrade, C.M.S., 2005. Forage peanut (Arachis pintoi): a high yielding and high quality tropical legume for sustainable cattle production systems in the Western Brazilian Amazon. In: International Grassland Congress, Dublin.

Verdade, L.M., Penteado, M., Gheler-costa, C., Dotta, G., Rosalino, L.M., Pivello, V.R., Piña, C.I., Lyra-Jorge, C., 2014. The conservation value of agricultural landscapes. In: Verdade, L.M., Lyra-Jorge, C., Piña, C.I. (Eds.), Applied Ecology and Human Dimensions in Biological Conservation. Springer, Verlag Berlin Heidelberg, pp. 91–102. http://dx.doi.org/10.1007/978-3-642-54751-5.

Veysset, P., Lherm, M., Bébin, D., Roulenc, M., 2014. Mixed crop–livestock farming systems: a sustainable way to produce beef? Commercial farms results, questions and perspectives. Animal 8, 1218–1228. http://dx.doi.org/10.1017/S1751731114000378.

Walker, R., Moran, E., Anselin, L., 2000. Deforestation and cattle ranching in the Brazilian Amazon: external capital and household processes. World Dev. 28, 683–699.

Wanniarachchi, S.D., Voroney, R.P., Vyn, T.J., Beyaert, R.P., MacKenzie, A.F., 1999. Tillage effects on the dynamics of total and corn-residue-derived soil organic matter in two southern Ontario soils. Can. J. Soil Sci. 79, 473–480.

Wheeler, D.M., Ledgard, S.F., De Klein, C.A.M., Monaghan, R.M., Carey, P.L., McDowell, R.W., Johns, K.L., 2003. OVERSEER® nutrient budgets–moving towards on-farm resource accounting. In: Proceedings of the New Zealand Grassland Association, pp. 191–194.

Wheeler, D.M., Ledgard, S.F., Monaghan, R.M., McDowell, R., De Klein, C.A.M., 2006. OVERSEER nutrient budget model–what it is, what it does. Implement. Sustain. Nutr. Manag. Strateg. Agric. 231–236.

White, J.W., Hunt, L.A., Boote, K.J., Jones, J.W., Koo, J., Kim, S., Porter, C.H., Wilkens, P.W., Hoogenboom, G., 2013. Integrated description of agricultural field experiments and production: the ICASA version 2.0 data standards. Comput. Electron. Agric. 96, 1–12.

Wilkins, R.J., 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. Philos. Trans. R. Soc. B Biol. Sci. 363, 517–525. http://dx.doi.org/10.1098/rstb.2007.2167.

Zanatta, J.A., Salton, J.C., 2010. Soil carbon sequestration affected by no-tillage and integrated crop-livestock systems in Midwestern Brazil. Rev. Bras. Ciênc. Solo 210–212.