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Sustainable Intensification of Agriculture in the Argentinean Pampas: Capture and Use Efficiency of Environmental Resources

Octavio P. Caviglia[1,2*] • Fernando H. Andrade[3]

[1] INTA EEA Paraná. Ruta 11. Km 12,5 (3100) Paraná. Argentina
[2] Facultad de Ciencias Agropecuarias –Universidad Nacional de Entre Ríos. Ruta 11. Km 10 (3100) Paraná. Argentina
[3] INTA Balcarce-FCA Univ Nac de Mar del Plata CC 276, (7620) Balcarce, Argentina

***Corresponding author*: * ocaviglia@parana.inta.gov.ar**

ABSTRACT

Future human needs for food and fiber should be fulfilled mainly through the agricultural intensification on the actual cultivated land, pursuing an economically viable, socially acceptable and environmentally sustainable system. The objectives of this review are to: i) briefly describe the current cropping systems of the Argentinean Pampas, ii) discuss the reliability of cropping system intensification practices and to, iii) analyze the extent of the improvement in the use of water and solar radiation by incorporating cropping system intensification practices in the Argentinean Pampas. Current cropping systems in the Argentinean Pampas largely rely on summer crops, including soybean as the most widespread crop. The unbalanced cropping sequence of the Pampas has several aspects that threat their sustainability and efficiency. Sustainable intensification of agriculture in the Argentinean Pampas rely on a more intense use of cultivated land and environmental resources, such as rainfall and solar radiation, using an appropriate set of agronomic practices aiming to higher grain production focused on environmental concern. Since there is little scope for further increase in resource capture and use in the typically well managed single crops of the Pampas, the improvements will be strongly associated with higher levels of intensification, cultivating crops more frequently than before, and using the available resources during the winter season. Increases in water and radiation use efficiency would, however, be more related to the inclusion of more efficient crops involved in the sequence. Owing the north to south decreasing gradient of the length of growing season in the Argentinean Pampas, the choice of the more adequate cropping strategy to sequence intensification can be quite different.

Keywords: land equivalence ratio, radiation use efficiency, soybean, sustainability, water use efficiency
Abbreviations: C: **N**, carbon: nitrogen ratio; **ISI**; intesification sequence index; **LER**, land equivalence ratio; **RP**, radiation productivity; **RUE**, radiation use efficiency; **RY**, relative yield; **SOC**, soil organic carbon; **WP**, water productivity, **WUE**, water use efficiency

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INTRODUCTION

Increasing world population will raise food and fibre demand in the next years, if incomes per capita remain at least stable. Since there are few chances to add new arable land to cropping and there is a critical need to stop the "extensification" of agriculture on fragile ecosystems (Gregory *et al.* 2002), future needs should be fulfilled mainly trough an increased production on the current cultivated land (Evans 1993).

In contrast to the Malthusian view, it has been proposed that one of the most important driving forces to intensification is the population pressure (Boserup 1965, 1981). In this view, the resource shortage or the demand increase will compel people to adopt innovations, aiming to meet the need for goods. Thus, agriculture intensification would be a natural response to demographic pressure and the concomitant increase in food and fiber demand.

There is a general agreement that future human needs should be met through the agricultural intensification on the actual cultivated land if the protection of natural, fragile ecosystems is aimed, (e.g. Gregory *et al.* 2002; Cassman *et al.* 2003; Sadras and Roget 2004). Moreover, standardized protocols, like life cycle assessment (LCA) to achieve the environmental evaluation and potential impacts associated with a product or service over its life cycle (ISO 1997) applied to agricultural production, give an important weight to land use (Brentrup *et al.* 2004a, 2004b).

Agriculture in the Argentinean Pampas has been widely expanded and intensified in the last years, increasing total

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national production of cereals and oil crops. A considerable concern, however, has recently been evidenced over several aspects associated with the sustainability of the process of expansion and intensification of the agriculture, mainly those related to natural resource conservation.

The objectives of this review are to: i) briefly describe the actual cropping systems of the Argentinean Pampas, ii) discuss the reliability of cropping system intensification practices and to, iii) analyze the extent of the improvement in the use of water and solar radiation by incorporating cropping system intensification practices in the Argentinean Pampas.

AGRICULTURAL SYSTEMS IN THE ARGENTINEAN PAMPAS

The Argentinean Pampas (situated between 28 and 40°S and 68 and 57°W), one of the most important areas for agricultural production in the world, is a vast region of *ca.* 52 million ha of suitable land for agriculture and cattle production (Hall *et al.* 1992; Viglizzo and Roberto 1998). The Pampas has a warm temperate climate with adequate to less than adequate rainfall. Mean annual rainfall declines from SW to NE, ranging from 400 mm in the SW to more than 1200 mm in the NE, whereas the rainfall regime shifts from monsoonal in the northwest to more evenly distribute in the southeast (Hall *et al.* 1992). Mean annual temperatures increases from *ca.* 13.5 in the south to 18.5°C in the north of the region (Hall *et al.* 1992).

Soils of the Argentinean Pampas belong predominantly to the order of Mollisols, being Argiudols and Haplustols the most representative great groups of soils. Most soils are developed from loessic sediments, and show a gradient in texture from sandy and sandy-loam in the southwest to clay and clay-loam in the northeast (INTA-SAGyP 1990).

Current cropping systems in the Argentinean Pampas largely rely on summer crops, including soybean (*Glycine max* [L.] Merr.) as the most widespread crop that reaches 55-60% of cropped area of Buenos Aires, Cordoba, Entre Ríos, Santa Fe and La Pampa provinces (**Fig. 1**). The proportion of soybean on cropped area has remained fairly stable for the last 5 years (SAGPYA 2009), indicating that paddocks are cultivated, in average, almost 3 out of 5 years with soybean, although there are many areas within the Pampas where soybean proportion is higher, tending to monoculture. Winter crops, in contrast, only span on a small proportion of cropped area (22%).

The simplification of the systems, through the availability of gliphosate-resistant, transgenic soybean and the massive adoption of no-till (Satorre 2005), associated with low production cost, as compared to cereals, were the key factors that drove the dramatic increase of soybean cropped area.

Land tenure is another important issue involved in the widespread adoption of soybean as the predominant crop, since a considerable fraction of owners (40-70%, varying among areas) rent their land to highly specialized growers who are committed to plant and harvest soybean. As rent contracts are frequently agreed in a fixed amount of soybean (from 0.6 to 1.6 t ha^{-1}) there are minimal chances for other crops to be selected, in order to compensate that important cost.

The unbalanced cropping sequence of the Pampas has several aspects that threat their sustainability and efficiency. In fact, although monoculture of any crop is not an encouraged agronomic practice, high frequency of soybean in the crop sequences could turn the balance of carbon and other elements in the soil negative, leading to soil deterioration and degradation.

In fact, soybean residues have a low carbon: nitrogen (C: N) ratio, in contrast to cereals, conducive to a faster decomposition that, in addition to a low or moderate amount of crop residue, promotes a net low C input to the soil. Results of long-term experiments carried out in the South-Eastern Pampas have confirmed that cropping sequences,

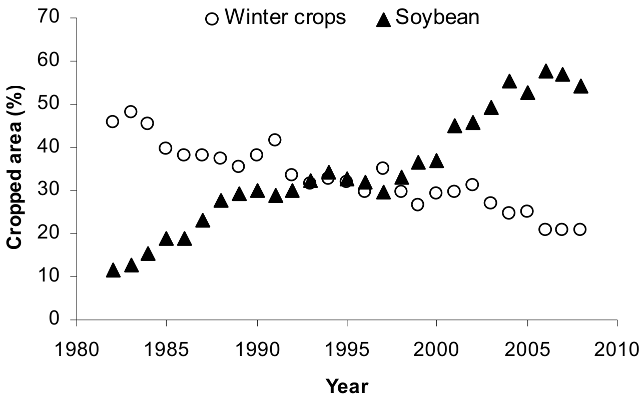

Fig. 1 Percentage of cropped area (period 1982-2008) in the Argentinean Pampas (provinces of Buenos Aires, Cordoba, Entre Ríos, Santa Fe and La Pampa) occupied by soybean and winter crops. Created from published data (SAGPyA 2009).

including a higher frequency of soybean, have a more intense reduction of soil organic carbon (SOC) than those sequences with a more balanced crop composition (Studdert and Echeverria 2000).

Although cultivation leads to a loss of SOC when land shifts from natural ecosystems to agriculture (Paul *et al.* 1997; Studdert *et al.* 1997; Studdert and Echeverria 2000), the process can become more intense if the sequence includes a high proportion of crops with low residue contribution and high C: N ratio, like soybean or sunflower (Studdert and Echeverria 2000).

While the amount of N that can be biologically fixed annually, could be as high as 200 kg ha^{-1}, commonly it only represents 50-60% of the soybean N demand (Salvagiotti *et al.* 2008). In a recent review made on a widespread dataset, the balance between N fixed and crop need was negative in 80% of cases (Salvagiotti *et al.* 2008), although the authors suggests that the estimation of balance can become close to neutral if an estimation of below ground contribution is included.

High N requirement for high yielding cereals as maize, wheat and sorghum, in the context of a low grain/fertilizer price relation, is a further reason involved in the high soybean adoption.

In the Argentinean Pampas extractable phosphorus (P) critical level for soybean is often lower than for cereals (usually 10-12 vs 15-20 ppm P Bray). Growers that sow soybean in rented land frequently manage the P fertility under a criterion of sufficiency, i.e. applying the minimum amount of fertilizer to avoid P deficiencies. In consequence, the decision to diversify the crop sequence with cereals has the implicit need to increase the cost of P fertilizer in order to reach their higher critical level. Fertilizers represent the most important fraction of the cereal production cost in the Pampas (Satorre 2005).

Consequently, estimations of the nutrient balance in the Pampas that include biological N fixation indicated that only 22-37% of N and 48-87% of P are replenished by inorganic fertilizers (Satorre 2005; Barbagelata and Melchiori 2007).

Cropping systems based in a single crop per year waste an important fraction of in-growing season or annual available resources (Caviglia *et al.* 2004; Coll *et al.* 2007). Within a cropping season, poor capture and efficiency in the use of water and radiation are associated with low leaf area during the establishment and senescence phases of single crops (Caviglia *et al.* 2004). Although several agronomic practices that shorten the period to reach the maximum canopy cover have been successful to improve the resource capture (Steiner 1986; Cooper *et al.* 1987; Board *et al.* 1994; Barbieri *et al.* 2000; Caviglia and Sadras 2001), there is very limited scope to further improve the in-season resource capture by single crops in the typically well managed crops of the Argentinean Pampas (Caviglia *et al.* 2004). At the single crop level, therefore, further yield improvements should become more from increasing resource use efficiency than from increasing resource capture.

In comparison to single cropping, intensification by use of multiple cropping can dramatically increase the resource capture and efficiency in the land use (Trenbath 1976, 1986; Hook and Gascho 1988; Fukai 1993; Caviglia *et al.* 2004).

Cropping systems intensification in the Pampas could, therefore, provide an improved efficiency in the use of resources and lands coupled to a reduction in the pressure on the more fragile ecosystems. Since intensification by use of multiple cropping has implicitly included other crops than soybean with higher C:N ratio and higher resource capture to produce biomass, a remarkable impact on the net balance of C could be expected.

SUSTAINABLE INTENSIFICATION OF AGRICULTURE

Improving crop yield per land unit and time has been usually defined as cropping system intensification (e.g. Cassman 1999; Gregory *et al.* 2002; Sadras and Roget 2004), although its meaning is fairly controversial. The more traditional view assumes that intensification includes any increase in productivity through an increased input use (e.g. Gregory *et al.* 2002) without an explicit concern about system sustainability, conservation of surrounding natural resources, and the welfare and health of rural and urban population.

The use of high input level is frequently associated with the idea of irrational use or misuse of chemical inputs. According to this view, intensification of agriculture seems not to be compatible, or at least somewhat contradictory, with sustainability.

The meaning of intensification is strongly associated with the classic economics, since it indicates a more intense use of the production factors, i.e. land, human labour and capital. Thus, those production systems that include a strong use of labour and capital per land unit, as horticulture for instance, are frequently recognized as intensive systems. In the same way, those systems characterized by a moderate or low use of labour and capital per unit land are called extensive.

In the traditional view of intensification it is often recognized that, implicit in the process, the specialization or simplification in the production has been increasing, which results in a reduction in the number of crop tending to monoculture (Matson *et al.* 1997).

There are, however, other views of the intensification like Boserup's (1987) who defined it as the gradual process in the land use that makes cultivation possible, at a given area, more frequently than before. This definition involves the use of less and/or shorter fallow periods.

Sustainable intensification of agriculture can be defined as the process that uses environmental resources (water, solar radiation, nutrients) more intensely, maintaining or increasing crop yield per unit area and using chemical inputs in a rational way. As we pointed out before, since there is a little scope for a more intense use of resources at the single crop level in the Pampas, the main way to increase the capture of available resources is shortening the fallow period through cultivating more crops per unit time and land.

Ecological principles that require management adaptation to the local conditions and the increase of plant and animal biodiversity level are implicit in this novel concept of sustainable intensification of agriculture for the Argentinean Pampas (Altieri 1999). This concept also includes all management strategies called "sustainable practices" such as balanced fertilization, integrated pest management, no-till, cover crops, terraces for soil conservation, among others.

The concept of sustainable intensification is similar to the "ecological intensification" defined by Cassman (1999) and to type III of intensification outlined by Gregory *et al.* (2002), in the sense that they also aim at profit improvement and consider key environmental issues, including the more efficient use of suitable lands. Sustainable intensification adds, however, the issues of cropping intensity aiming to use more intensely the environmental potential productivity. The concept contrasts however, with Gregory *et al.* (2002), who have sentenced that increasing global demand for food, shall be met by increased yields per area with a smaller contribution from increases in cropping intensity.

It has been recognized that many of the management strategies associated with sustainable intensification of agriculture will result in increases of SOC levels (Matson *et al.* 1997; Gregory *et al.* 2002), with an associated improvement in soil fertility, aggregates formation, buffer capacity, pesticide adsorption, air exchange, biological activity and water-holding capacity (Seybold *et al.* 1998). In consequence, the role of soils could be changed from source to sinks for atmospheric carbon dioxide (Matson *et al.* 1997; Lal *et al.* 1998).

Sustainable intensification of agriculture is therefore, in nature, associated with: i) an increased utilization of environmental resources through the use of a higher fraction of growing season, i.e. an increase in cropping intensity, ii) the use of sustainable practices oriented to preserve natural resources and human life health and, iii) maintained or increased crop productivity per unit land.

Alternatives of cropping systems intensification

Human attitude tending to adopt conservative strategies oriented to minimize risk seems to be similar in the different cropping systems (Sadras and Roget 2004).

Accordingly, the widespread adoption of soybean in the Pampas responds to: i) high plasticity in response to changes in environmental conditions leading to a more stable yield than cereals, ii) considerable low cost, and iii) high grain price. Physiological and morphological features that confer more plasticity to soybean, in contrast to other crops, have been deeply pointed out elsewhere (Andrade and Ferreiro 1996; Vega *et al.* 2001a, 2001b; Vega and Sadras 2003).

Adoptable farming systems accounting for the sustainable intensification principles need to consider the inclusion of crops that confer stability, productivity, and profitability. The exclusion of soybean from the cropping systems of the Argentinean Pampas is, therefore, not a realistic proposal.

The use of winter season crops emerges as a feasible option to match the concept of sustainable intensification with the preceding considerations. Including winter crops into crop sequences could improve the efficiency in the utilization of largely wasted resources without excluding soybean.

Options to sustainable intensification of cropping systems in Argentinean Pampas should be based, therefore, in a practical and profitable combination of winter and summer crops in order to improve the ability to capture and use resources more efficiently. Winter crops adapted to the Pampas conditions are spring wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), flax (*Linum ussitatissimum* L.), canola (*Brassica napus* L.), and some grain legumes like dry peas (*Pisum* sp.) and lentil (*Lens* sp.). Spring wheat in the Pampas is the main winter crop (>95%) and it is expected that most of the wheat paddocks are sown with soybean shortly after harvest. The area of wheat/soybean double crop is therefore estimated based on wheat area representing *ca*. 20% of cropped area (**Fig. 1**).

Although soybean is the main crop following winter crops, there is a considerable scope to use maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and sunflower (*Helianthus annus* L.). Agronomic practices, especially genotype selection, should be explored to make the option of winter-summer double cropping more realistic.

In the Southern Pampas, the yield of late-sown soybean in double cropping systems is severely restricted by short free-frost period and the important fall in photoperiod and

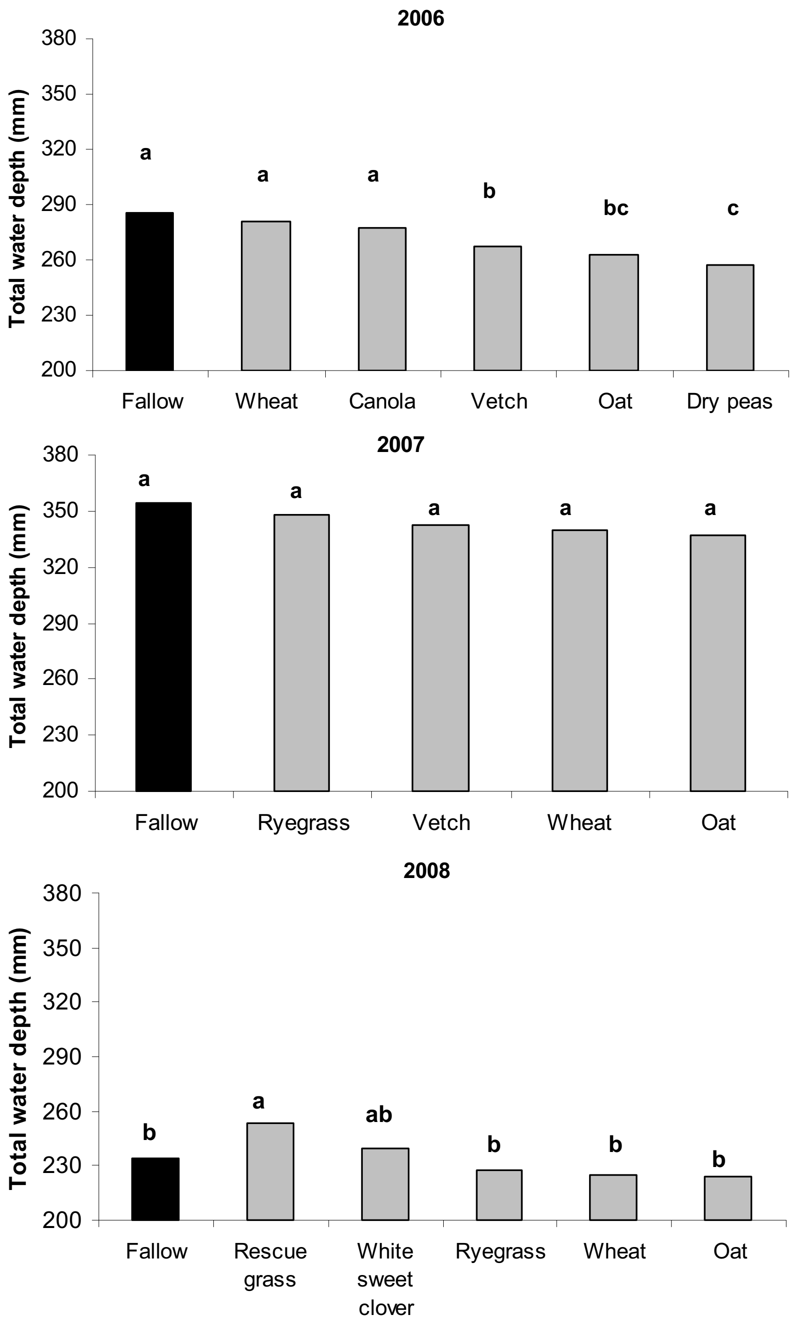

Fig. 2 Total water depth (up to 1 m) in cover crops (unpublished data) at killing date (*ca*. 20-30 Sept) in the Northern Pampas (Paraná, 32ºS; 60ºW) from 2006 to 2008. Rescue grass: *Bromus catharticus*., White sweet clover: *Melilotus alba*, Ryegrass: *Lolium multiflorum*, Wheat: *Triticum aestivum*, Oat: *Avena sativa*., Vetch: *Vicia villosa*, Canola: *Brassica napus*, Dry peas: *Pisum sativum*.

temperature that leads to drastic reduction in seed number and seed mass (Calviño *et al.* 2003a). Agronomic background and management alternatives to mitigate yield reductions in late-sown, double cropped soybean have been widely reported in that environment (Calviño and Sadras 2002; Calviño *et al.* 2003a, 2003b).

The strategy of relay intercropping, i.e. sowing soybean into standing green wheat during grain filling, has been proposed as a way to better adjust the double crop cycle to the environment (e.g. Caviglia *et al.* 2004). Similarly, other cropping strategies based on multiple cropping have been proposed in the Southern Pampas in order to improve the land and the resource use efficiency through intercropping maize or sunflower with soybean cultivars short enough to fit into the growing season, but avoiding the overlapping of their respective critical periods for yield determination (Calviño, pers. comm.).

Owing the north to south decreasing gradient in the length of growing season in the Argentinean Pampas, the choice of more adequate cropping strategies to sequence intensification can be quite different. Probably, in the northern area the most suitable choice could be to incorporate sequential winter-summer double crop, whereas in the southern area could be necessary to overlap the crops cycles to fit in the shorter growing season through the inclusion of winter-summer or summer-summer relay intercrop.

It is widely accepted in the Argentinean Pampas that soybean yields are higher when the crop grows as a sole crop in the year than when it is sown as a second crop after wheat (Calviño *et al.* 1999, 2003a). Promissory experiences in the Northern Pampas, however, have shown that the inclusion of a previous winter cover crop does not affect soybean yield and water content at the time of sowing (**Fig. 2**) if killing date of the winter cover crop is before or at the beginning of the spring rainfall period. Thus, environmental resources can be more efficiently used to increase the input of C balance into the soil without a reduction of the most profitable crop.

The use of cover crops is, therefore, another alternative to cropping systems intensification in the Argentinean Pampas that meets the principles of sustainable intensification. In addition to higher resource capture efficiency and their contribution to the balance of SOC, cover crops protect the soil from wind and water erosion.

The use of cover crops has been widely proposed aiming different purposes. For example, as break crops to reduce the impact of soilborne pathogens, nematodes and root diseases (Abawi and Widmer 2000), as catch crops, sown after the main crop to reduce the remaining nutrient leaching from the soil profile (Weinert *et al.* 2002; Dean and Weil 2009), as nutrient source to the following crop (Frye *et al.* 1985; Utomo *et al.* 1990) both as cover crop (Andraski and Bundy 2005; Zotarelli *et al.* 2009) and green manure incorporated to the soil (Cherr *et al.* 2006), and for weed suppression (Al-Khatib *et al.* 1997; Reeves *et al.* 2005), among other objectives.

Most of the alternatives for sustainable cropping intensification in the Argentinean Pampas seem to be centred in the winter season, since the most profitable, productive crops occupy the summer season. For summer crops, the growing season is often constricted by the frost free period, in contrast to winter crops which can use a considerable amount of resources during the frost period. Moreover, cover cropping can be used in environments with considerably shorter growing season and more severe winter conditions than in Argentinean Pampas as, for instance the US Corn Belt (e.g. Griffin *et al.* 2000). Thus, if the sustainable intensification principles are adopted, the winter season would be devoted to confer sustainability to the agricultural system, whereas the summer season would be advocated to farm profitability.

Useful indicators of intensification

Two valuable indicators can be used to quantify the performance of the intensification process: Land equivalent ratio (LER) and intensification sequence index (ISI). Land equivalent ratio (LER) indicates the land area required for sole crops to produce the same amounts of grain as the multiple crop. LER is estimated as the sum of the relative yield (RY) of the crops involved in the multiple crop, RY in turn is calculated as the ratio between crop yield in the multiple crop and the yield of sole crop (Trenbath 1976, 1986).

A LER higher than 1 usually indicates that multiple crop is advantageous in relation to sole crop. The fractions that exceed the unity express the percentage of additional land that hypothetically would be needed to produce, with sole crops, the amount of grain obtained with multiple crops. For example, a LER of 1.55-1.65, a typical performance of a wheat/soybean double crop in the Argentinean Pampas (Caviglia *et al.* 2004), indicates that 55-65% more land would be required to produce the same amount, with wheat and soybean as sole crops, than that produced by the double crop.

Intensification sequence index (ISI) is an adequate and very intuitive indicator that expresses the number of crop per year in a given sequence (Farahani *et al.* 1998). Crops sequences in the Argentinean Pampas that include wheat/soybean double crop, usually show an ISI greater than 1 (**Fig. 3**). There is a wide variation in ISI among agricultural regions in the world. The index ranges from as low as 0.5 in the Great Plains (USA), where fallow-wheat is a widespread sequence (Farahani *et al.* 1998), to 3-4 in Asia, where it is possible to grow four sequential rice crops in a year (Evans 1993). In many areas of South and North America wheat/soybean double crops have been already adopted to a variable extent, whereas in South-Asia the rice-wheat double crop system has been widely expanded (Evans 1993; Timsina and Connor 2001).

CAPTURE AND USE EFFICIENCY OF ENVIRONMENTAL RESOURCES

Cropping intensification in the Southern Pampas improved resource capture on an annual basis. Wheat/soybean double crops increased the capture of radiation and water as compared with sole crops (**Fig. 4**) (Caviglia 2005).

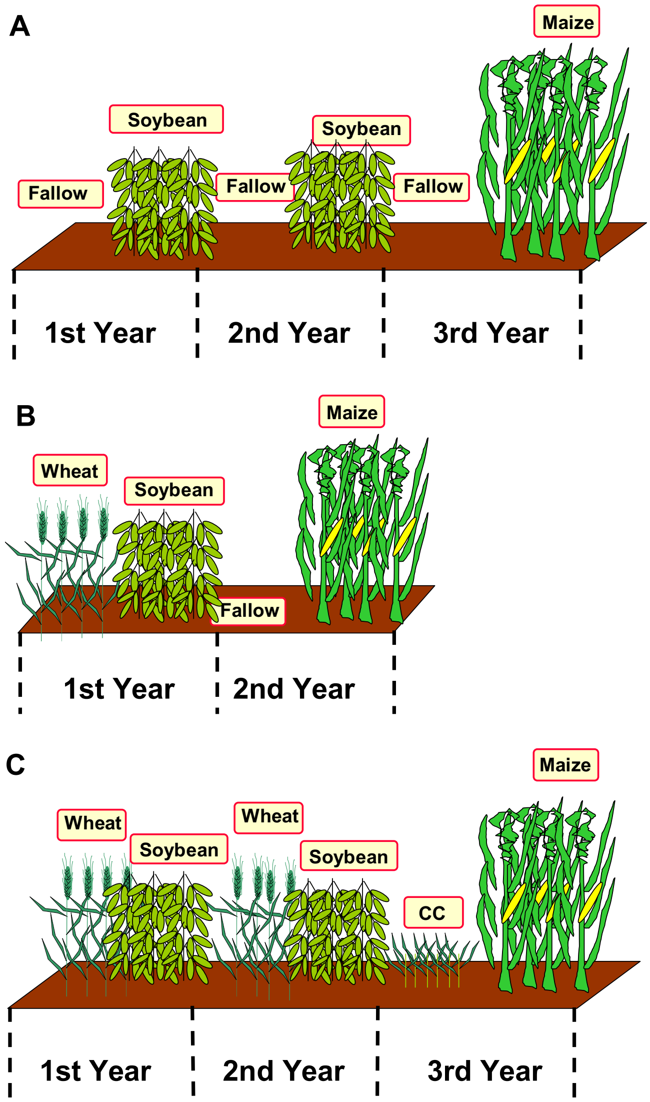

Fig. 3 Typical crop sequences of the Argentinean Pampas differing in intensification level, as quantified by intensification sequence index (ISI). (**A**) Sequence length = 3 years, # crops = 3, ISI = 1; (**B**) Sequence length = 2 years, # crops = 3, ISI = 1.5; (**C**) Sequence length = 3 years, # crops = 6, ISI = 2. CC: winter cover crop.

The capture of annual precipitation by crops increased from 26-51% in sole crops to 53-71% in wheat/soybean double crops, whereas the capture of annual solar radiation increased from 24-31 to 38-44% (**Fig. 4**). Even though double crops used as much as 53-71% of annual precipitation (**Fig. 4**), they only intercepted *ca.* 40% of the incident solar radiation. This reflects the better matching of cropping cycle to rainfall, and the different nature of resources. Water can be stored in the soil, thus attenuating offsets between resource availability and crop demand (Caviglia *et al.* 2004). The capture of radiation is, in contrast, dependent on canopy size and structure at a given time and there are no compensatory mechanisms for recovering light that was not intercepted by the canopy.

Water and radiation capture by other options of multiple crops in the Southern Pampas, like maize/soybean and sunflower/soybean relay intercrops, was slightly or not increased compared with sole crops (Coll *et al.* 2007). Similarly, Díaz *et al.* (2007) reported a similar annual radiation capture of a maize/soybean relay intercrop and their sole crops in an experiment carried out in the Northern Pampas.

The overlap of the life cycle of summer crops growing in relay intercrops confer only a limited advantageous performance to capture the potential productivity available

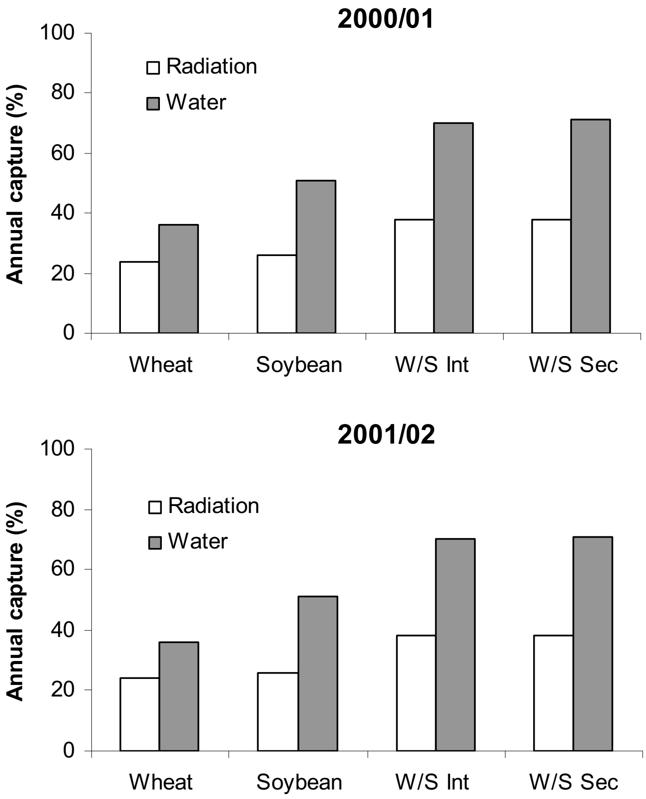

Fig. 4 Water and solar radiation annual capture by wheat and soybean as a sole crop and wheat/soybean (W/S) double crop in relay intercropping (Int) or sequential (Sec) cropping. Values expressed as percentage of annual available resources. Experiment carried out in 2000-2001 and 2001-2002 in the Southeastern Pampas (Balcarce, 38ºS, 58ºW). Adapted from Caviglia (2005).

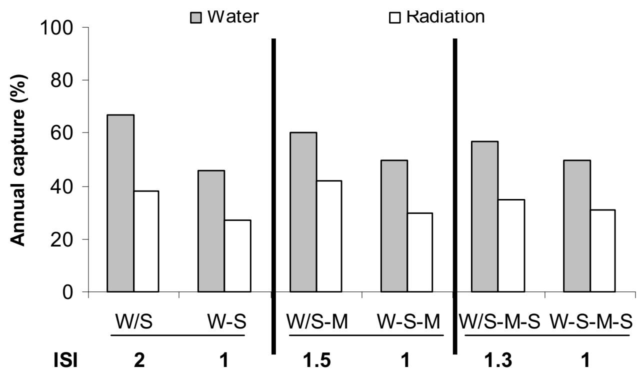

Fig. 5 Water and solar radiation annual capture by couple of sequences that differ in intensification level as quantified by ISI (intensification sequence index). Values expressed as percentage of annual available resources. Bars represent the average of 30 rotation phases (period 1971-2002) in a simulation study at the Southeastern Pampas (Balcarce, 38ºS, 58ºW). W: wheat, S: soybean, M: maize; W/S: wheat/soybean double crop. Adapted from Caviglia (2005).

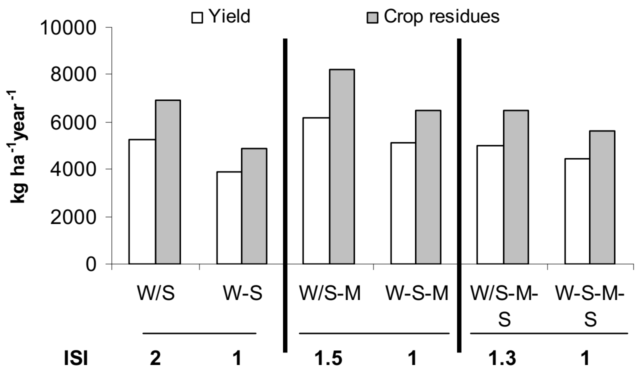

Fig. 6 Annual grain yield and annual crop residues of couple of sequences that differ in intensification level as quantified by ISI (intensification sequence index). Bars represent the average of 30 rotation phases (period 1971-2002) in a simulation study at the Southeastern Pampas (Balcarce, 38ºS, 58ºW). W: wheat, S: soybean, M: maize; W/S: wheat/soybean double crop. Adapted from Caviglia (2005).

during the entire growing season, specially solar radiation. Lack of improvement in efficiency of this option to resource capture as compared with the sole crop would be related to: i) the wide rows spacing (1.57 m apart) of the first crop, maize or sunflower, needed to sow two soybean rows (0.53 m apart), ii) the short period in which duration of the intercrop canopy exceeds those of the sole crops, since both intercrops and sole crops explore a similar portion of the growing season.

In sequences of the Southeastern Pampas with similar composition but differing in ISI, water and radiation capture was higher with increased level of cropping intensification through the inclusion of wheat/soybean double crop (Caviglia 2005). In fact, in a given sequence the increase of resource capture, water and solar radiation, was related to the level of ISI (**Fig. 5**).

Cropping intensification also increased the use of available water in the Great Plains (USA) (Farahani *et al.* 1998), where wheat-fallow, 2-year sequence is widely spread. Fallow length ranged from 14 to 21 months if spring or winter wheat, respectively, is included. Fallow in the US Great Plains and other regions such as West Asia, North Africa (Bolton 1981) or Israel (Bonfil *et al.* 1999) are largely inefficient to capture rainfall. The efficiency of rainfall storage ranges from 10 to 30% varying upon the use of soil and water conservation practices as no-till and weed control. The inefficiencies of fallow are related to evaporation loses during summer months therefore, Farahani *et al.* (1998) proposes including a summer crop to use water that otherwise would be lost.

Using an analogy with economics, resource productivity (i.e. grain mass per unit of annual available resource) can be analysed as the product of capture and efficiency factors (Caviglia *et al.* 2004). Thus, water productivity (WP, grain mass per unit of annual available water) can be estimated as the product of annual capture (i.e. the ratio between evapotranspiration and annual available water from rainfall and soil storage at planting) and water use efficiency (WUE, i.e. the ratio between grain yield and evapotranspiration). Similarly, radiation productivity (RP, grain mass per unit of annual available photosynthetically active radiation) can be estimated as the product of annual capture (i.e. the ratio between intercepted photosynthetically active radiation and annual available radiation) and radiation use efficiency (RUE, i.e. the ratio between grain yield and intercepted photosynthetically active radiation).

Water productivity (WP) is similar to "efficient water use" as defined by Pierce and Rice (1988) and, if we assume available water equals annual precipitation, WP equals precipitation use efficiency as defined by Farahani *et al.* (1998).

This analytical approach is useful to provide insight regarding how double cropping could increase annual productivity of water or radiation. In the Southern Argentinean Pampas, both WP and RP were higher in wheat–soybean double crops than in sole crops, largely related to improved capture of resources, whereas differences between sequential and relay wheat–soybean double crops were minor (Caviglia *et al.* 2004). Water use efficiency and RUE were minor sources of variability in resource productivity when scaling up from a single to a double crop or a sequence level (Caviglia *et al.* 2004; Caviglia 2005).

WUE and RUE were unrelated to ISI when the intensification tool was the inclusion of wheat/soybean double

Table 1 Performance of several multiple crops in the Argentinean Pampas. Data was calculated from Caviglia *et al.* (2005); Calviño *et al.* (2005); Coll *et al.* (2007); Diaz *et al.* (2007).

Multiple Crop	RY 1st crop	RY 2nd crop	LER
M/S Intercrop	70-90%	40-50%	1.10-1.40
SF/S Intercrop	75-95%	30-60%	1.20-1.45
M/S Sequential	74-93%	10-48%	1.03-1.29
W/S Sequential	90-100%	40-80%	1.30-1.80

LER: land equivalence ratio, RY: relative yield; M: maize, S: soybean, SF: sunflower, W: wheat

crop (Caviglia 2005). The improvement in WUE and RUE was recorded in sequences that contain maize, since there was a positive, linear relathionship between maize proportion (i.e. # maize crops per year) and WUE (Caviglia 2005). This could be attributable to highly efficient C4 photosynthetic metabolism and low energetic value of grain composition of maize as compared to wheat and soybean. Differences among cereals and oil crops in use efficiencies resulting from photosynthetic metabolism and energetic cost to produce oil and protein in grain are discussed elsewhere (Andrade 1995; Sinclair and Muchow 1999; Caviglia *et al.* 2004).

The improved resource capture for a better match of crops to environmental offer and the inclusion of more efficient crops, such as maize or sorghum (C4 photosynthetic metabolism), seems to be the emerging issues to design crop sequences oriented to high resource productivity. These issues are, in nature, strongly associated with the concepts of sustainable intensification pointed out before.

An increased resource productivity has implicit a higher total biomass production, leading to an improved return of crop residues to the soil (**Fig. 6**) which would be valuable to turn the SOC balance into positive or at least less negative. A similar result was reported for the US Corn Belt where winter/summer double crops had a total shoot biomass production 25% greater than the sole maize crop (Heggenstaller *et al.* 2008).

The extraction of nutrients will possibly increase as a consequence of higher resource productivity of the cropping systems. Then, the intensification of cropping systems would require increased fertilization rates and/or integration with nutrient recycling mechanisms (Heggenstaller *et al.* 2008).

Reported performance relative to land use efficiency has been variable among multiple crop options and areas within the Pampas (**Table 1**). LER improvements in intercrops using summer species results mainly from the interaction between components rather than from increase in resource capture, since the scope for this strategy is truly limited (Coll *et al.* 2007). Higher LER were reached in multiple crops when winter and summer species were cropped in sequence or in relay intercropping (Caviglia 2005). The increase in land use efficiency in the latter is probably associated with the striking increase in resource capture (Caviglia *et al.* 2004). Thus, the improvement in resource capture through intensive cropping appears as one of the most important issues that underlies the greater land use efficiency in multiple crops.

CONCLUSIONS

Sustainable intensification of agriculture in the Argentinean Pampas relies on a more intense use of cultivated land and environmental resources, like rainfall and solar radiation, using an appropriate set of agronomic practices aiming to higher grain production in an economically viable, socially acceptable and environmentally sustainable system.

An important issue to meet the requirements of sustainable intensification is the design of cropping sequences oriented to use the available resources during the winter season, since agriculture in the Argentinean Pampas largely relies on summer crops.

Since there is little scope to further increase in resource capture and use in the typically well managed single crops of the Pampas, the improvements will be strongly associated with higher levels of intensification, cultivating crops more frequently than before. Increases of water and radiation use efficiency would, however, be more related to the inclusion of more efficient crops involved in the sequence.

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