Improving Alfalfa Varieties and Cropping Systems in a Bioeconomy Framework

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Bioeconomy framework is appropriate to revisit the protein issue, the possible contribution of alfalfa to the world protein demand and the objectives for alfalfa breeding and cropping systems.As underlined by Mathijs et al (2015), the key principles of bioeconomy arefood first, sustainable yields, cascading approach and circularity.

Food is a key issue worldwide due to the constant demand increase in relation to world population and the increasing competition with non-food uses, such as bioenergy and biofuel or industrial purposes.

Cascading means that the biomass may be fractioned to further valorise every component when they show contrasting biochemical composition or physical properties. Circularity is extremely relevant to agriculture when considering that the manure from animal production may become either as a source of pollution or a main source of soil fertility.

These principles are very relevant to protein production and uses. Indeed, because of the uniqueness of protein for human diets, there is a long-term tension on the market of all protein-rich commodities. Considering circularity, the core of protein production and consumption is the N cycle. This biogeochemical cycle has potential negative environmental impacts, with possible air and water pollution and strong risks of greenhouse gas emission. The key aspects is that the N_2 molecule is stable thanks to the triple link and extremely abundant in the atmosphere. Reactive nitrogen must be available to produce proteins, but this reactive nitrogen may generate negative environmental impacts (UNEP and WHRC, 2007).

Protein issue: how to meet world demand?

Proteins are unique in the human diet, as they are the only source of amino acids that are, for part of them indispensable for human life, humans being not able to synthesize amino acids. In absence of substitution, they must be obtained from the diet. The nutritional value of animal proteins is higher than that of plant protein because the equilibrium between essential amino acids better fits human requirements.

Figure 1 summarizes the worldwide situation of protein use and need over the last decades and with a projection over the next 20 years. Individual consumption of animal proteins increases more quickly than the one of plant proteins, with mean values in 2010 of 31 and 48 g/hab/day respectively. Considering the world population increase, this means a world consumption of animal and plant proteins of 80 and 120 Mt/year respectively.

The protein efficiency of animal production shows contrasting value from 2.31 for milk (2.31 g of plant protein are needed to produce 1 g of animal protein in milk) to 9.84 for cattle and sheep red meat and intermediate values of 2.77 and 3.3 for chicken and pork meat production (BIPE-Sofiproteol, pers. com.). Taking into account the consumption of the various animal products worldwide, it may be calculated a mean protein efficiency of 3.59, even if this value must be taken with caution. Considering this conversion and the FAO projection for human consumption in the next decades, it appears that the world demand in plant protein in 2030 could exceed the 2010 value by 180 Mt, which represents the protein production of about 180 Mha of soybean. This would be a tremendous increase compared with the present situation, which is likely to induce strong competition for this unique resource.

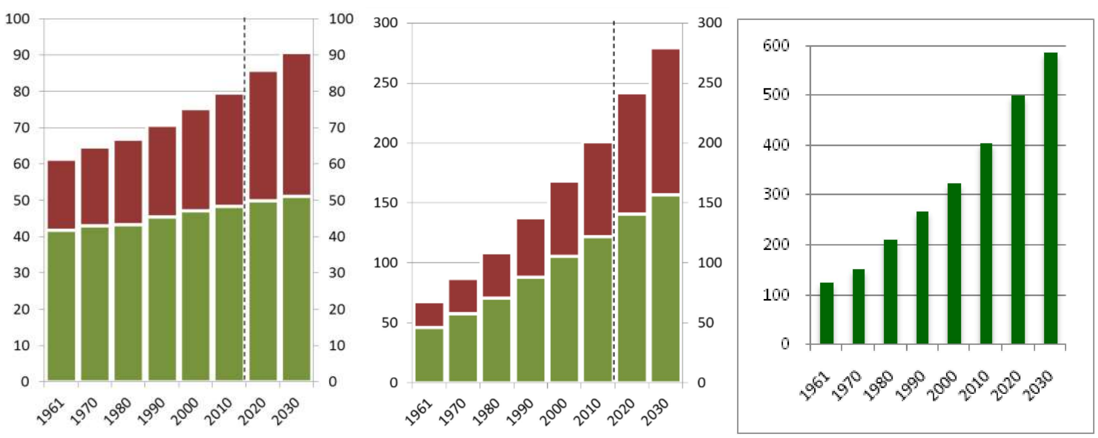

Figure 1: Protein consumption in the world and consequences on the need for production of plant protein. a) mean daily consumption of animal (red) and plant (green) proteins (in g/hab/day); worldwide consumption of animal (red) and plant (green) proteins (in Mt/yr); c) consequences on the need of plant proteins. Source: FAOSTAT, own calculation

Closing the loop: protein production and environmental impacts

The systemic pattern of proteins and nitrogen is represented in Figure 2. The plant proteins are used for human nutrition, either directly or after conversion into animal proteins. In the case of monogastrics, the use of additional essential amino acids (lysine, cysteine, methionine, tryptophan…) in the diet made it possible to significantly improve efficiency of conversion of plant proteins.A small share of the plant proteins may be used for technological uses in the Bio-based industries (BBI).

In a given country, the plant proteins may come from protein-rich feedstuff obtained from grain processing, mainly grains from oil crops such as soybean, rapeseed or sunflower. In Europe, despite the large increase of production of rapeseed for production of biofuels, the main share is from imported soybean. In the rest of the world, soybean cakes are the main share, mainly produced in North and South America.

Plant proteins are also obtained from other grain crops, such as cereals and grain legumes or from forage crops. The potential protein production per hectare of these various grain and forage crops ranges from 0.5 to 2.3 t/ha under the Western European conditions, the highest protein production being obtained from alfalfa, while production from all grain crops range from 0.5 to 1.3 t/ha (Figure 3). The main difference among these grain crops is the protein content that determines the possible use as protein source, especially in animal production.

In animal production, a significant part of the nitrogen present in the diet as proteins is lost in manure (urine and faeces). For grazing cattle, nitrogen is directly absorbed by the growing plants in the grasslands. Risks of leakage have been documented for grasses or mixtures of grasses and forage legumes (Vertès et al, 2010). For animals in house, manure is collected, stored with risk of ammonium emission, and used on crops and grasslands as a source of organic nitrogen fertilizer. The only other source of nitrogen is mineral nitrogen obtained thanks to industrial synthesis, the Haber-Bosch process being the only industrial process that produced ammonitrate thanks to a chemical reaction at high temperature and high pressure to break the triple link. Natural gas is used for this reaction and thus generates CO_2 emission.

For plant growth, all crops require nitrogen, that is provided by fertilization or obtained by the grain or forage legume crops through symbiotic nitrogen fixation, thanks to the symbiosis with the rhizobium bacteria in the nodules.

When mineral or organic nitrogen fertilizers are supplied, a small share of the nitrogen is lost as N_2O, this nitrous oxide being a strong greenhouse gas, with a global warning effect of 298 (the global warming effect of CO_2 being 1).

Legume crops will adapt the symbiotic fixation to their need, i.e. uptake the available mineral nitrogen and fix the additional nitrogen required for their growth. For the non-fixing crops, N fertilisation is most often provided in excess, leading to N residues at the end of the growing season. The crop rotations and the possible intercrops are essential to avoid leakages of nitrates.

This is part of the ecosystem services provided by alfalfa and other forage and grain legumes (Schneider and Huyghe, 2015). For alfalfa, one additional important ecosystem service is the beneficial effect of presence of alfalfa on the honeybee populations, especially when a differentiated management is implemented, i.e. when a small share of the alfalfa field is not harvested at one cut to maximize flowering and production of nectar and pollen.

This loop, which is briefly summarized here above, shows all the possible sources of variation in this complex system. As far as alfalfa is concerned, it is especially important to consider 1) the potential of protein production per unit area and 2) the nitrogen balance at the level of the crop rotation when alfalfa is involved.

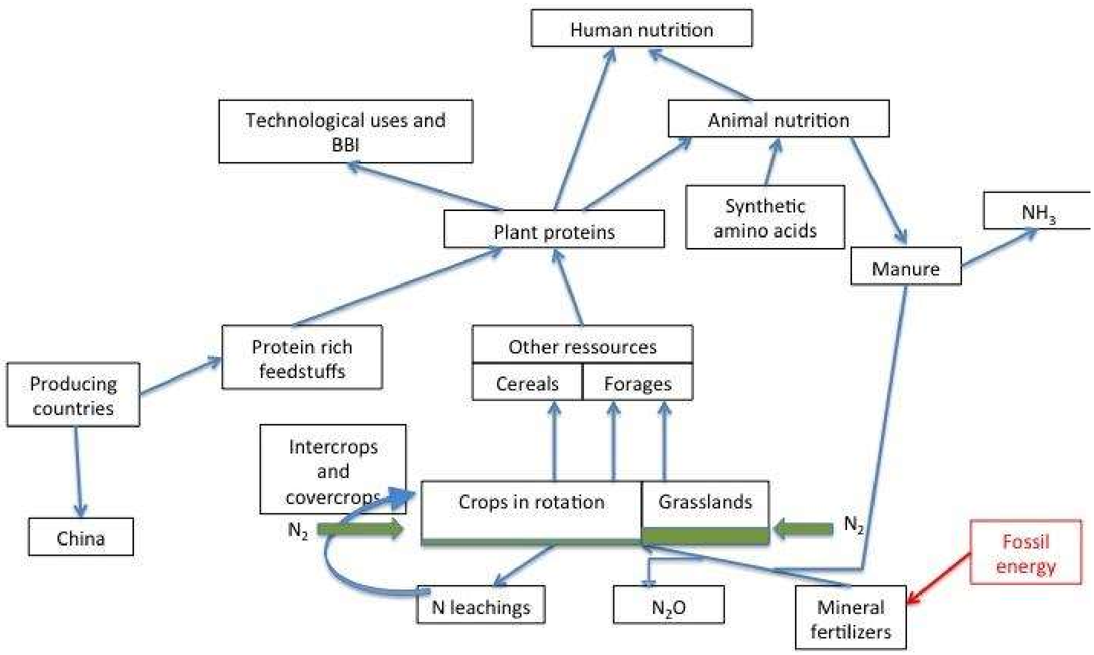

Figure 2: Schematic representation of protein and nitrogen flux in a bioeconomy approach

Potential of protein production

Figure 3 shows the protein production from various crops in France. For the cereals and the oil crops (rapeseed and sunflower), the production of proteins is between 0.5 and 1t/ha. For the grain legumes, it is between 1.0 t and 1.3 t/ha for pea, faba bean and lupin, and lower for soybean and lentil, this last crop being exclusively used for human consumption. The highest protein productions are achieved for alfalfa (2.2 t/ha), red clover (1.8 t/ha) and temporary grasslands with mixtures of grasses and legumes (1.7 t/ha), while perennial grasses produce 1.0 t of proteins per ha.

For the non-fixing crops, this production is obtained with the use of mineral nitrogen fertilizers, while for the grain and forage legumes as well as the temporary grasslands with mixtures, the nitrogen is provided through symbiotic fixation.

The proteins produced from these various sources show contrasting composition and properties. Comparing grain legumes and forage legumes, while dry grains may be stored during long periods of time, it is necessary to dry forage to save the protein quality from alfalfa leaves. If stored as silage or haylage, part of proteins may be degraded, leading to a lower quality for feeding ruminants. When comparing various modes of alfalfa conservation, dehydration proved to be the most efficient for getting high feeding value because of the low ruminal protein degradability.

The second main difference sits in the protein composition. While the grain proteins include a wide range of molecules, the main alfalfa protein is Rubisco. Thus, the development of technologies for separation and extraction of proteins from alfalfa leaves for further uses in human nutrition would be highly beneficial, following the principle of cascading.

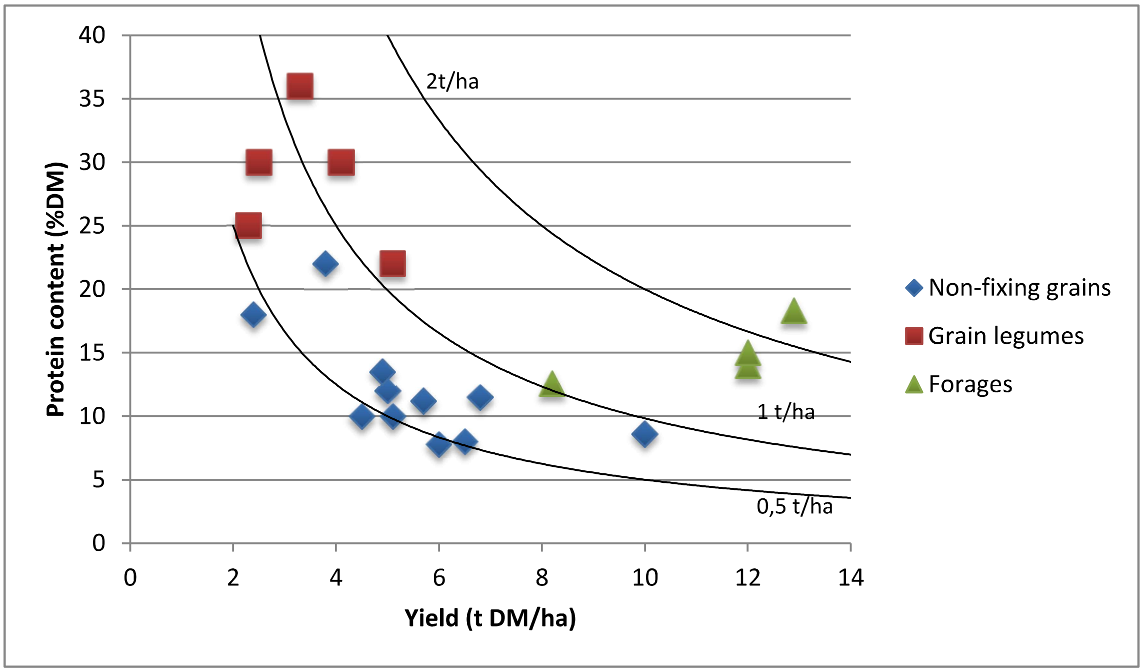

Figure 3: Relationship between grain or biomass yield and protein content for various grain and forage crops in France. The values of dry matter yield for forages are calculated for a 3-years cycle including the year of establishment. The curves indicate iso-yields of proteins. Sources: Agreste, CTPS

Consequences for alfalfa breeding and cropping systems.

Increasing the protein yield in alfalfa breeding has been a major concern since the early breeding step. It was first achieved by breeding for yield, either directly through the growth potential, or indirectly through the improvement of disease resistance. More recently, the selection for protein content in the biomass was performed, and in 1994, this trait became a selection criterion for variety registration on the French national catalogue. For registration on this national catalogue, the fibre content has also been taken into account since 2007 as an estimator of forage digestibility (Huyghe and Tabel, 2009).

The computation of all varieties tested for registration in France over the last 10 years in comparison with a common control (the variety Comete that has been among the top 3 varieties in the 2000'ies), shows an absence of negative correlation between DM yield potential measured over a 3 years trial period in 8 sites and the mean protein content (Figure 4). It also shows a trend towards an increasing production of proteins, especially among the most recent candidate varieties. Indeed, some varieties are producing on average 10% more protein per ha than the control. This is mainly achieved through an increase in the potential of biomass production. The use of protein content as a registration criterion mainly avoids seeing a negative drift in protein content, that could endanger the use of alfalfa forage for feeding some types of animals.

Most attempts to genetically increase protein content for a given level of dry matter production were poorly effective, such as through production of multifoliolate genotypes (Juan et al, 1993; Annicchiarico et al, 2015), the main driver of the protein content being the biomass accumulation and the sward structure, as a consequence of variation of the leaf/stem ratio (Lemaire et al, 1992), this leading to a low heritability (Guines et al, 2002). The fall dormancy of the varieties will determine their growth rhythm, and as a consequence, in combination with the harvest date, their main feature regarding protein content.

As a consequence, it is essential to think together plant breeding and cropping systems. Indeed, at the level of a farm or a territory, the adapted combination of varieties and harvest date is essential for maximising the protein production.

The harvest is a critical phase in alfalfa due to the high risk of protein losses during the harvest steps. When harvested as silage or haylage, and because of the poor carbohydrate content, the acidification process is very slow. Forage conservation and preservation of protein may be improved by either pre-drying or use of preservatives and additives. When producing hay, leaves may be lost during the drying process, while when dehydrated, the energy cost is directly related to the water content and pre-drying on the field is an essential issue for reducing these energy cost. Thus, harvesting equipment and its ability to preserve leaves and to speed up the drying rate are essential issues, whatever the conservation system.

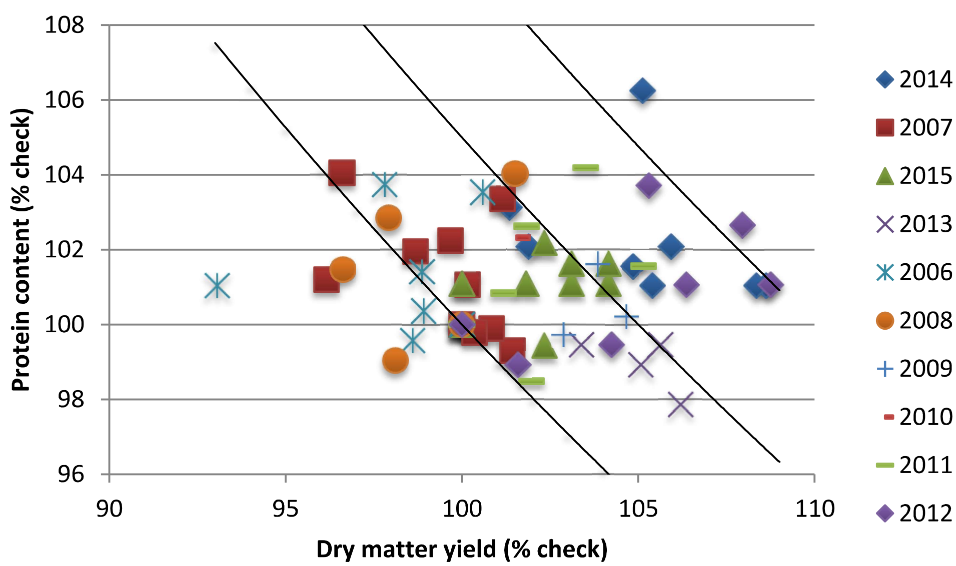

Figure 4: Relationship between dry matter yield and protein content, expressed in % of a common check) for candidate varieties to registration over the last decade in France.

The production of protein per ha is thus an essential issue. However, when considering the animal nutrition and the protein efficiency, it is important to consider protein quality. In forage legumes such as alfalfa, leaf proteins are soluble, thus highly degradable in the rumen when alfalfa is fed as fresh forage or degraded in silage when this storage mode was chosen.

The harvesting technology is essential for determining protein quality. In alfalfa, conservation as silage degrades the protein value in comparison to fresh forage. When preserved as hay, the protein value is improved because of the lower protein degradability. It is further improved by dehydration because of the further reduction in protein solubility.

Dehydrationis a particularly effectivepreservation processto increasethe availability ofproteinsper hectare.Fora yield of13 tDM / ha with a mean protein content of 20%, alfalfa produces2.6 toftotal proteinor 1.04 t of metabolisable protein valuable for milk or meat production by ruminants (Vérité and Peyraud, 1989) that is equivalent to the production of metabolisable protein of 1.82hectares ofsoybean crop. Ifthe entire productionof thishectare is dehydrated,the production ofmetabolisable proteinfor ruminantsbecomes the equivalentof2.51haof soybean. Otherusagescan beenvisaged bya cascadeoperation, if proteins are extracted from leaves to produce a protein concentrate and stems are dehydrated. The extraction ofalfalfa leafproteinallows to obtainaprotein concentratethat can be used for human or monogastric nutrition(about 0.6tofprotein /ha, i.e. equivalent to 0.6 ha of soyabean) anda residue whichstill coversthe equivalent of1.9hasoybeanequivalentto feedruminant.

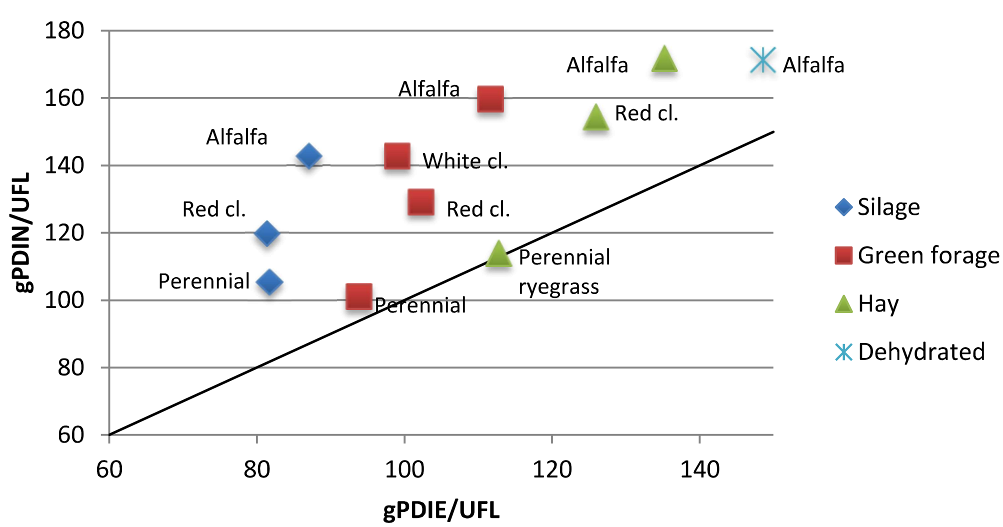

Figure 5 : Change in protein value of forage legumes (alfalfa, red clover, white clover) in comparison with perennial ryegrass according to harvest system. Source : Inra, 2007

Alfalfa and nitrogen balance of the cropping systems

The manure is a source of nitrogen fertility for the whole cropping system. However, the reduction of the quantity of manure through improved protein efficiency is beneficial at the scale of the production system as it avoids losses of N as N_2O.On the opposite, alfalfa is highly beneficial to the N balance of the crop rotations. Indeed, the residues of the alfalfa crops may contribute up to 350 kg of N to the N budget of the subsequent rotation, with a slow release over the new two years because of the slow mineralisation of the highly lignified alfalfa taproot (Justes et al, 2001). The management of the crop rotation is essential to benefit from this potential N resource.

As the symbiotic fixation does not contribute any N_20 emission, and because of the large N_2 symbiotic fixation, insertion of alfalfa is a crop rotation appears to be one of the most efficient way to reduce greenhouse gas emission in agriculture, with possible beneficial economic returns (Pellerin et al, 2013).

Conclusion

Alfalfa is a major source of proteins, because of its high production potential and the adaptation of the species to a wide range of soil and climate conditions and resistance to pests and diseases. Genetic gains for protein production per unit area are mainly achieved through increase in biomass production. Alfalfa forage is highly suited for feeding ruminants, especially dairy cattle, because of the high protein content and the high voluntary intake of the forage. The forage digestibility is then to be taken into account and improved, to ensure a good use of the proteins.

Forage technology may provide a huge improvement of the protein quality and as a consequence increase its efficiency for feeding animals and by the way reducing the losses of reactive nitrogen. Biomass technologies may also be implemented for extracting proteins in order to use then directly in human nutrition, thus directly contributing to the huge worldwide challenge of protein resource.

A bioeconomy approach also points out the importance to think about circularity. This may be achieved by considering alfalfa as part of the plant and animal production system. Indeed, alfalfa is a large provider of N for the following crops in the rotation, where it contributes to a significant reduction of the production of greenhouse gas emission.