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Lucerne (Alfalfa) in European Cropping Systems

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Abstract

This chapter reviews knowledge on the agronomy, genetics, feeding value and harvesting methods used for lucerne (alfalfa; *Medicago sativa*), which is the temperate climate legume species with the highest protein yield. It has agronomic advantages (high forage production, adequate persistency and drought tolerance) and provides a high-quality feed for ruminants. Lucerne also has positive impacts on the environment such as soil structure, nitrogen fertility, carbon storage, and plant and animal biodiversity. Lucerne production supports sustainable farming systems. Besides seed production that generates significant economic activity, novel uses of lucerne for human or animal health or energy production are also being investigated. Proposals for measures to increase lucerne cultivation in European farming systems are provided.

Introduction

Lucerne (alfalfa; *Medicago sativa* L.) is a perennial herbaceous forage legume cultivated under a wide range of climatic conditions, from oases in North Africa to Siberia. The stems and leaves, which are rich in protein, are harvested several times a year. The combination of high-quality forage production and biological nitrogen fixation (BNF) addresses the dual challenge of food security and resource conservation. There is therefore renewed interest in the crop. Lucerne is favoured particularly for its beneficial effects on soil structure and fertility, nitrogen (N) and carbon (C) cycles, protection against erosion, pesticide and herbicide use, water

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quality and biodiversity. Lucerne cropping for seed production is an additional activity that ensures the availability of high-quality seed of adapted cultivars.

This chapter provides an overview of the origin of lucerne, its cultivation and use, and provides updated information on physiological, genetic and technical aspects related to its development, cropping and provision of ecosystem services.

Botany, Biology and Main Characteristics

Lucerne is phylogenetically close to clovers (*Trifolium* sp.), pea (*Pisum sativum* L.) and faba bean (*Vicia faba* L.). The seed is small (2 g/1000 seeds) and is sown at a high density (about 20 kg of seeds/ha). A seedling is formed by a primary root and primary axis. The first leaf is unifoliolate while the subsequent leaves are trifoliolate. The establishment of a lucerne stand is quite slow, but after 3 months, the plants form vigorous erect leafy stems that can reach 120 cm in height. After cutting, new stems are formed from the axillary buds of remaining stem sections and/or from the collar at the base of the plant. Over several cutting cycles, a large crown and a deep rooting system are established. The taproot explores deep layers of soil (potentially exceeding 2 m depth). The allocation of assimilates (sugars and proteins) to the root determines the stand persistency. Because of intense competition among plants for light and nutriments, the plant density decreases over time, especially during the first 6 months after sowing, to about 300 plants/m^2. Winter survival is mainly determined by the degree of autumn–winter dormancy, which is linked to responses to reducing day length that results in low growth activity.

Lucerne is an out-crossing species (i.e. it is allogamous). Various morphological characters limit self-pollination before flower tripping is carried out by pollinating insects. Self-pollination is not restricted by incompatibility genes but seeds mostly originate from cross-pollination. Self-fertilization leads to inbreeding depression, so heterozygosity predominates in all populations.

Area of Production, Yield, Harvest Methods and Use

Lucerne is grown in pure stands in Europe on nearly 2.5 million ha, of which over 65% are located in Italy, France, Romania and Spain (Table 11.1). About 140,000 ha in Spain, 90,000 ha in Italy and 80,000 ha in France are grown to produce lucerne for drying or high protein (17–22%) pellets. Estimates that consider legume–grass mixtures (usually excluded from country statistics) suggest that lucerne is the most widely grown forage legume in 15 countries of south, east or west Europe (along with red or white clover in a few cases).

The crops are mechanically harvested after the budding stage and the forage (stems and leaves) is stored as hay or silage or dried in factories (Fig. 11.1). Lucerne is adapted to infrequent mowing. Grazing is also used in some regions, particularly in extensive systems because of its low cost. Although stands can persist for up to 10 years, the crops are usually harvested over a 3–5 year period.

Annual forage yields usually range between 4 t/ha and 15 t/ha, with three to seven harvests per year at 5–8 week intervals. Fewer harvests, usually with lower

Table 11.1. Production of lucerne in Europe: cultivated area and cultivated area as a proportion of the utilized agricultural area (UAA). The most widely used forage legume or legume mixture (main legume) in each country is also indicated. (From FAOSTAT, 2013; Eurostat, 2013; Annicchiarico *et al*., 2015.)

Country	Cultivated area (1000 ha)[a]	Proportion of UAA (%)	Mean yield (t/ha)[b]	Main legume[c]
Austria	13.9	0.5	2.4	Red clover
Bosnia-Herzegovina	35.8	2.3	1.8	Red clover
Bulgaria	64.6	2.1	7.1	Lucerne
Croatia	25.9	2.1	2.5	Lucerne
Cyprus	0.8	0.7	3.7	Lucerne
Czech Republic	67.1	1.9	13.7	Lucerne/red clover
Denmark	5.7	0.3	17.6	White clover
Estonia	10.5	1.2	4.5	Red and white clover
France	329.1	1.2	14.8	Lucerne/white clover
Germany	40.4	0.2	11.4	Red clover
Greece	129.3	3.2	3.7	Lucerne
Hungary	132.7	3.0	11.7	Lucerne
Italy	716.4	5.8	10.5	Lucerne
Lithuania	4.8	0.2	7.8	Red clover
Luxembourg	0.3	0.2	13.4	–
Macedonia	18.4	1.9	2.2	Lucerne
Netherlands	5.9	0.3	7.0	White clover
Poland	33.6	0.3	10.4	Red clover
Romania	332.6	2.6	6.0	Lucerne
Serbia	200.0	4.0	5.5	Lucerne
Slovakia	52.2	2.8	10.9	Lucerne
Slovenia	2.6	0.6	2.4	Lucerne/red clover
Spain	248.5	1.1	15.8	Lucerne
Total	2470.9	1.7	10.0	Lucerne

[a] Average for years 2008–2011 according to FAOSTAT, except for: Bosnia-Herzegovina, Croatia, Lithuania, Macedonia (average of 2008–2009) and Greece (2007), which are based on Eurostat; data for Serbia and part of data for France are based on national sources.
[b] Based on UAA values for 2010 in Eurostat or other European Union (EU) documents, and reported lucerne growing data.
[c] Data from Annicchiarico *et al*. (2015).

annual production, are used either in cooler regions or under drought conditions. In temperate climates, lucerne can produce more harvested crude protein per unit area than any grain legume crop (pea, faba bean or soybean) (Huyghe, 2003).

Protein content varies between 15% and 25% of dry matter, depending mainly on the harvest stage. For ruminants, lucerne offers a combination of high voluntary intake, high protein content, good digestibility, and rumen buffering that prevents acidosis. About 10% of lucerne production is used in monogastric animal diets (pigs, poultry, rabbits), where it offers the advantage of high levels of omega-3 fatty acids, carotenoids and mineral nutrients. Lucerne pellets can be included up to 10–20% on a dry matter basis in these diets. This inclusion is limited by either antinutritional compounds and/or excessive fibre content. Introduction

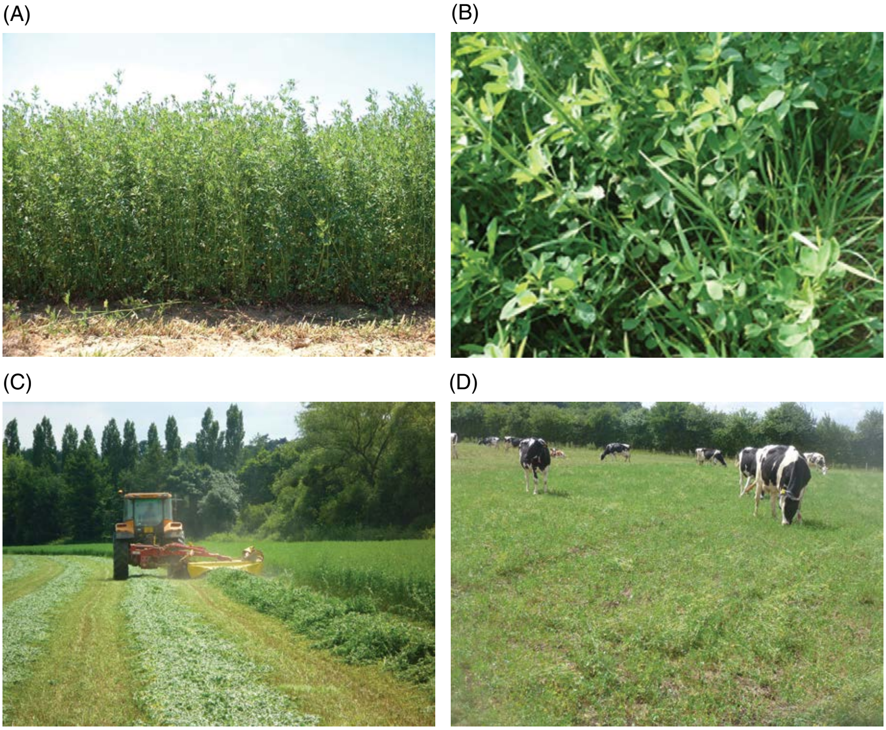

Fig. 11.1. Typical production scenes. (A) Lucerne field at early flowering stage. (B) Lucerne–grass mixture. (C) Mechanical harvest: on the left, some swathes after cutting by only a rotary disc mower and on the right a swathe after cutting with a rotary disc mower with conditioning rollers. (D) Grazing of a lucerne–grass mixture. (Photo credits: B. Julier (A, B) and G. Crocq (C, D).)

of lucerne into the diets of both ruminants and monogastrics is a way to significantly decrease the need for soybean meal.

Cultivation has declined over the last 50 years with the increased cultivation of maize for silage, enabled by a combination of maize breeding, synthetic N fertilization, pesticides and supplementation with soy. Recent increases in fertilizer and soy prices are leading to a reversal of this trend. A return to more mixed farming systems is also contributing to this turnaround.

Genetic Resources

Medicago sativa is a complex of eight diploid or autotetraploid subspecies (Quiros and Bauchan, 1988). The main subspecies are: (i) *sativa* (conventional cultivated lucerne), with purple flowers, a taproot and coiled pods; and (ii) *falcata*, with yellow flowers, fasciculate roots and curved pods. Cultivated material of subsp. *sativa* is tetraploid due to the vigour that tetraploidy confers.

Cultivated lucerne originates from between the Middle East and Central Asia where it may have been cultivated as early as in 9000 BC (Sinskaya, 1950). The history of domestication is not well known. Domestication resulted in an erect growth habit relative to the prostrate habit of wild populations (an adaptation to grazing). Lucerne as a cultivated crop was introduced into Europe with human migrations at various times: through Greece with the Medes, Italy with the Romans, and Spain with the Moors (Fig. 11.2). It became a popular forage species in Europe after the 15th century, from where it was introduced to America. Wild populations of subsp. *sativa* are present in the centre of origin and in Spain, while wild populations of subsp. *falcata* are widespread in Eastern Europe. Most European lucerne cultivars exhibit some degree of introgression from subsp. *falcata* germplasm, which has provided cold tolerance and variable flower colour. Molecular studies show that only 30% of the allele variation in wild populations is also found in cultivated populations (Muller *et al*., 2006). Persistent feral populations are frequent in Europe and North America, mostly along roadsides (Bagavathiannan *et al*., 2010). These populations may contain valuable adaptive traits, as suggested by the outstanding frost tolerance of a Canadian feral population.

Several countries in Europe maintain collections of perennial *Medicago* genetic resources, but wild populations are generally poorly represented. The European Cooperative Programme for Plant Genetic Resources (ECPGR), now coordinated by Bioversity International, was set up in 1980 to rationalize the conservation of genetic resources. The perennial *Medicago* collection contains 7874 accessions of 19 species. The Russian Federation hosts one-third of the collection, and tetraploid lucerne represents over 95% of the accessions, including cultivars (1920 accessions), landraces (1430), wild or feral populations (769) and breeding materials (1260).

Lucerne breeding programmes have largely used landrace germplasm adapted to specific environments as their genetic base. These adaptations provide germplasm to counter stresses and to more effectively exploit favourable conditions (Annicchiarico and Piano, 2005). This has a bearing on strategies for locating, evaluating and exploiting genetic resources (Annicchiarico, 2007).

Agronomy, Ecology and Crop Physiology

Establishment

Care in establishing the sward is critical to productivity and longevity of the crop. Summer sowing offers the opportunity to establish the crop just after harvesting the preceding crop. It requires adequate soil humidity and temperature during late summer and autumn so that the lucerne stand is fully established before winter frost. If such favourable conditions are not encountered, the lucerne crop is sown during spring to ensure successful establishment (Mauriès, 2003; Undersander *et al*., 2011). In any case, effectiveness of plant and sward development in the months after sowing is critical to productivity of the subsequent cropping year. Insufficient sward development from late summer sowing followed by early autumn frosts, reduces production in the following spring.

Lucerne requires well-drained soils and pH above 6 (ideally in the range 6.6–7.5) for optimal growth. Liming is recommended when soil pH is below 6.5. Due

Fig. 11.2. Lucerne introduction into Europe.

to the small size of the lucerne seed, seeding depth is critical and needs to be shallow (typically 1–2 cm). BNF in root nodules requires the presence of specific strains of rhizobia in the soil. Seed inoculation with *Rhizobium meliloti* (or use of inoculated seeds) is essential where there is not a recent history of lucerne cropping.

Lucerne is very susceptible to light competition from weeds during its establishment (Mauriès, 2003; Undersander *et al.*, 2011). A low seedling development due to early intense weed competition is very detrimental to subsequent lucerne production and longevity. Therefore, weed control following sowing is a critical step for proper sward establishment. Weed control can be achieved either chemically (although few herbicides are now permitted) or mechanically. Mixing forage grasses with lucerne may help to reduce and control weed invasion during the establishment phase, provided that the grasses are sown at a density low enough to avoid a level of light competition detrimental to lucerne (Spandl *et al.*, 1999). Lucerne may also be undersown in a cereal (wheat, maize) or an oilseed crop (sunflower) that is harvested for grain, leaving space for the lucerne plants to continue developing and producing during the following years.

Lucerne is an autotoxic species. Lucerne leaves produce water-soluble chemical compounds that leach from crop residues and are retained in the upper soil layer. These inhibit seed germination and seedling development (Chon *et al.*, 2006). This autoxicity means that an interval of 3–4 years between lucerne crops is required. This also interrupts the cycle of several pests and thus reduces the risks of disease or pest damage.

Dry matter production and leaf area expansion

Under non-limiting conditions, lucerne above-ground growth is linearly related to the amount of solar radiation intercepted by the canopy (Lemaire and Allirand, 1993) (Fig. 11.3). Shortening days and low temperatures in autumn induce allocation of more carbohydrate to roots, explaining the lower radiation use efficiency in terms of above-ground growth observed during this period (Khaity and Lemaire, 1992).

The interception of solar radiation depends on the leaf area index (LAI), which increases linearly with thermal time after each crop harvest. A LAI of 3 (3 m^2 leaf area/m^2 ground area) intercepts 90% of incoming light and is reached approximately 300°C days (base 0°C) after mowing under non-limiting conditions (Gosse *et al.*, 1984). In addition to temperature, the residual leaf area left after the harvest and the stage of development of the crown buds also influence the rate of leaf area expansion during regrowth.

Shoot growth and forage quality

As stems elongate, the leaf:stem ratio decreases, which has consequences for the quality of the harvest because leaves have a higher protein content and digestibility

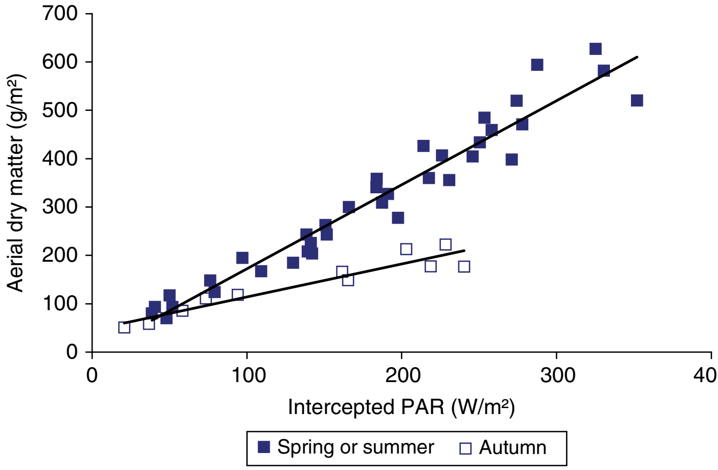

Fig. 11.3. Relationship between above-ground dry matter and the sum of intercepted photosynthetically active radiation (PAR, W/m²) for the spring and summer cuts and for the autumn ones.

than stems (Lemaire and Allirand, 1993) (Fig. 11.4). Late harvests increase yield but decrease the leaf:stem ratio and, hence, the digestibility and N concentration of the harvested biomass.

Short photoperiods and cool temperatures in autumn reduce above-ground growth and favour allocation to roots. During this period, autumn-dormant genotypes produce short decumbent shoots and have higher concentrations of sugars and proteins in their buds and roots than non-dormant genotypes (Cunningham *et al.*, 1998). In autumn, lucerne stems are generally short but very leafy, generating a low forage production but a high forage quality.

Water and nutrient requirements

Lucerne is acknowledged as more drought-tolerant than other perennial legumes because of its deep rooting system (Peterson *et al.*, 1992). However, it is an opportunistic water user that is best suited to soils with a high water reserve. In contrast to species adapted to drought stress, it exhibits low stomatal closure in the early stages of drought (Durand, 2007). After the initial growth phase, BNF in nodulated plants supplies enough fixed N for optimal growth (Lemaire *et al.*, 1985). Annual fixation rates from 85 kg N/ha to 360 kg N/ha are reported (Frame, 2005).

Due to the relatively high yield potential of lucerne under cutting management, large quantities of nutrients are removed in harvested biomass, so particular attention is required to maintain soil fertility in order to achieve high biomass yields (Mauriès, 2003; Undersander *et al.*, 2011). Maintenance of soil fertility is also critical for the longevity of the crop, particularly under poor and acidic soil conditions. Lucerne accumulates potassium (K) and phosphorus (P) at approximately 25 g/kg shoot dry weight and 2.6 g/kg shoot dry weight,

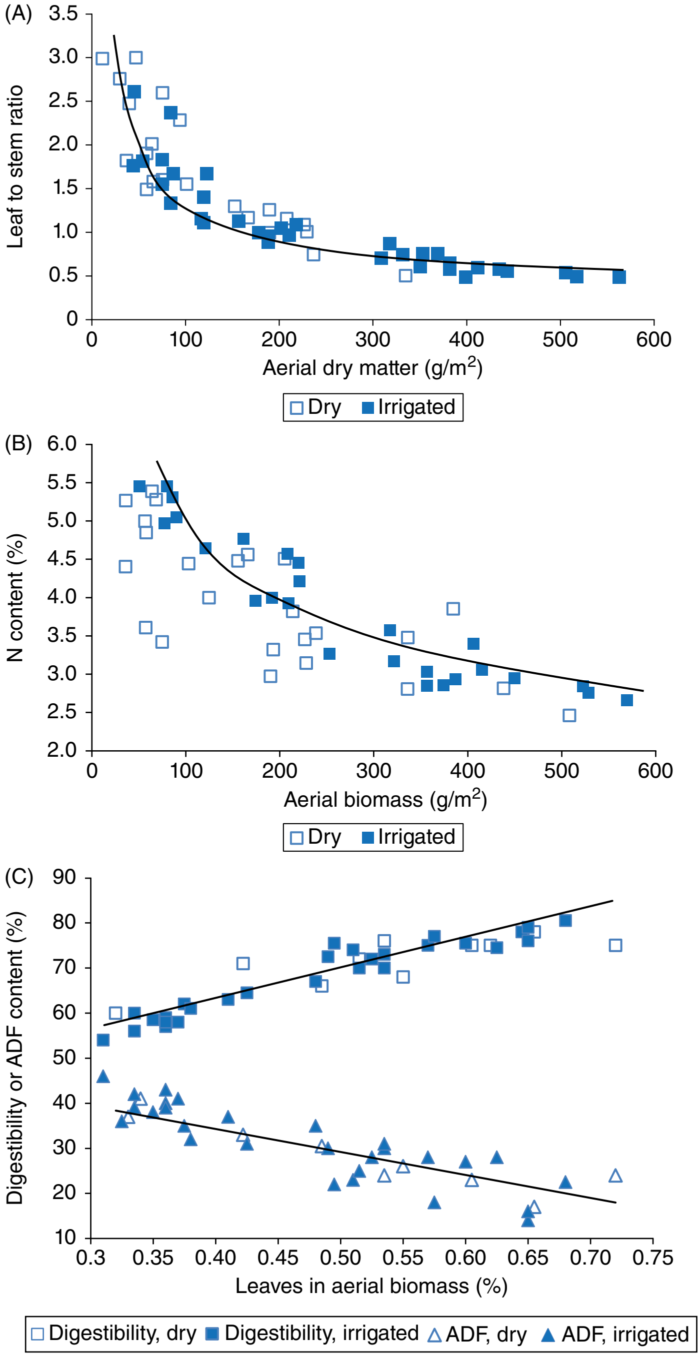

Fig. 11.4. Change in quality traits during dry matter accumulation. (A) Leaf to stem ratio as a function of above-ground dry matter. (B) Nitrogen (N) concentration as a function of above-ground dry matter. (C) Digestibility or acid detergent fibre (ADF) concentration as a function of the percentage of leaves in above-ground biomass. (From Lemaire and Allirand, 1993.)

respectively, corresponding to 30 kg of K_2O/t harvested biomass and 6 kg of P_2O_5/t harvested biomass. Application of sufficient P and K fertilizers is thus necessary to compensate for these high rates of removal, according to the soil availability of these minerals, which in turn depends on soil physicochemical characteristics and on management of the preceding crops. Similarly, attention to soil availability of other nutrients is required, in particular magnesium, sulfur and calcium, depending on soil characteristics.

Competitive ability and compatibility with grasses

Although lucerne is grown in pure stands in many instances, it is also commonly grown in mixtures with perennial grasses. Mixtures are generally as productive as pure stands under favourable cropping conditions. High-yielding lucerne cultivars in mixtures tend to be at a competitive advantage over grasses (Chamblee and Collins, 1988), so a 50/50 sowing rate frequently results in over 80/20 annual yield in favour of lucerne during the first years. The greater ability of lucerne to compete for light resulting from erect shoots, leaf angles and a large leaf area in the top layers of the canopy partly explains this difference. More balanced mixtures can be achieved through moderate N fertilization to improve grass growth and more frequent defoliation. The choice of grass species and lucerne cultivars is also of importance. Reasonably high-yielding lucerne cultivars with shorter stems, smaller leaves and higher branching ability provide a less aggressive companion crop for the grass (Maamouri *et al.*, 2015). Furthermore, favouring non-competitive interactions in the mixture, such as the transfer on fixed N from the legume to the grass, would also improve grass N nutrition and growth and thus the balance between species. Nevertheless, lucerne displays a rather less efficient N transfer than other forage legumes (Louarn *et al.*, 2015). Although lucerne can fix twice as much N as white clover, white clover is about five times more efficient at providing fixed N to the companion grass than lucerne. A significant diversity in root traits exists among lucerne cultivars, which remains to be exploited in terms of breeding for compatibility with grasses.

Reserves and defoliation management

After harvest, C and N reserves are mobilized from roots for about 6–10 days. Root reserves start to recover after regrowth has progressed but several weeks are generally required to restore them (Lemaire and Allirand, 1993) (Fig. 11.5). Lucerne is thus suited to an infrequent defoliation regime. Furthermore, root N reserves available at harvest influence leaf area expansion and the growth rate after defoliation (Avice *et al.*, 1997; Justes *et al.*, 2002). Flowering, although not physiologically related to reserve accumulation in the roots, is generally used as an indicator of adequate replenishment of root reserves to guide harvest scheduling. Increasing the mowing frequency reduces the yield of single harvests, the total annual yield and the crop persistence, while increasing the forage nutritive value. For example, in northern France, four harvests are effective, while five are likely to reduce the persistence (Lemaire and Allirand, 1993). Irrigation of lucerne in Mediterranean climates supports up to eight harvests.

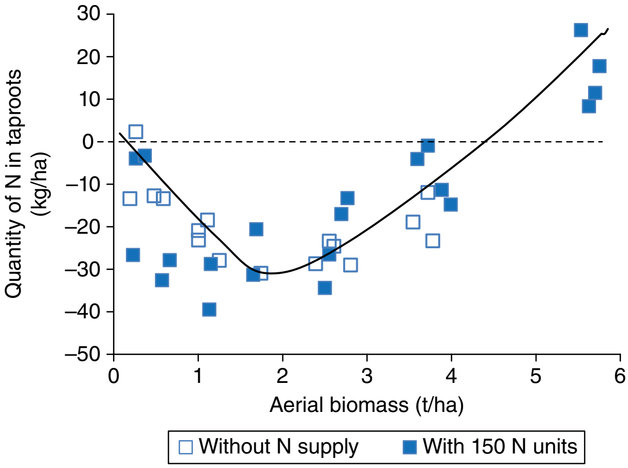

Fig. 11.5. Change of nitrogen (N) content in taproots as a function of above-ground biomass. (From Lemaire and Allirand, 1993.)

Breeding

Genetic progress

The rate of genetic progress for lucerne forage quality has been modest, namely, 0.2–0.3% per year in the USA and somewhat less in Europe (up to 0.15% per year) (Annicchiarico *et al.*, 2015), which is definitely lower than major grain crops such as wheat or maize. Recent breeding advance relates mainly to greater tolerance to major pests. Breeding progress for intrinsic yield potential is slow due to the perennial nature of the crop, long breeding cycles, and because increasing the harvest index is not a breeding option as it is in cereals. Breeding is also difficult because cultivars are populations rather than pure lines.

Cultivar structure

The biological characteristics (allogamy, impossibility to control pollination and inbreeding depression) facilitate the breeding of synthetic cultivars that exploit heterosis. Each cultivar is derived from four to 200 parents (a parent being an individual genotype, or a half-sib progeny obtained by open-pollination of one mother plant). Three to four generations of polycrossing (or inter-mating) are made to obtain the commercial seed. A cultivar is thus a population of related genotypes.

The only commercial genetically modified (GM) lucerne cultivar is a Roundup Ready cultivar registered in the USA in 2005 (which underwent a period of legal confrontation before being admitted to cultivation). A second GM cultivar with improved digestibility has been obtained by down-regulating lignin synthesis (Guo *et al.*, 2001; McCaslin and Reisen, 2012). The development of GM lucerne cultivars in Europe is expected to be met with public hostility strengthened by the risk of gene flow to feral or wild populations due to the reproductive system. However, for a few crucial traits that show no variation within lucerne, such as tannin content, a GM cultivar could be a real breakthrough.

Breeding targets

Autumn dormancy is important for winter survival. The cultivars adapted to northern Europe have a dormancy class ranging from 3 to 5 on a scale from 1 to 11. Cultivars adapted to European Mediterranean climates have a dormancy of 6 to 8. Within each dormancy class, breeding targets are mostly similar with some differences in emphasis. Forage yield is a major target. It is frequently tested over 2 production years (not including the sowing year). Stem length is an important trait, although stem diameter and stem number tend to compensate each other. Resistance to lodging is important, especially in the spring cuts for northern Europe, because it ensures that all the above-ground biomass is harvested. It is strongly related to stem diameter, a trait that is negatively correlated with voluntary intake by small ruminants.

Forage quality is also evaluated, with emphasis on protein content and fibre content. Even if quality traits tend to correlate negatively with forage yield, genetic variation is available (Julier *et al.*, 2000) and cultivars with high digestibility improve milk production in dairy cows (Emile *et al.*, 1997). Seed production is also important for propagation. The seed weight per inflorescence is a useful breeding criterion in selecting for high seed yield (Bolaños-Aguilar *et al.*, 2001).

Resistance to diseases is a major target, with genetic progress attained for response to verticillium wilt (*Verticillium albo-atrum*) and anthracnose (*Colletotrichum trifolii*). Resistance to stem nematode (*Ditylenchus dipsaci*) is also important. Tests in controlled conditions are available for all of these biotic stresses (Leclercq and Caubel, 1991; Julier *et al.*, 1996; Molinéro-Demilly *et al.*, 2007). Tolerance to other biotic stresses may be needed for specific adaptation. Screening tests in controlled conditions have been proposed for resistance to aphids (Girousse and Bournoville, 1994; Landré *et al.*, 1999) and sclerotinia rot (*Sclerotinia trifoliorum*) (Julier *et al.*, 1996).

Drought is a major constraint on yield, although drought tolerance has been only a minor breeding target so far. In most European regions, lucerne frequently experiences transient drought episodes during which an important objective is to maintain sufficient forage production. Modest levels of irrigation are used in southern Europe but the crop is not a priority where irrigation water is scarce. Genetic variation for adaption to drought or moisture-favourable conditions is wide in lucerne (Annicchiarico and Piano, 2005; Annicchiarico *et al.*, 2011). Different and partly incompatible morpho-physiological traits are associated with optimal plant adaptation to drought-prone and moisture-favourable conditions (Annicchiarico *et al.*, 2013).

Despite the degree to which acidic soils limit lucerne cultivation in Europe, no selection has been carried out to improve tolerance to low pH. Other legume species (clovers) are preferred for low pH soils. Cultivars that are tolerant of salinity have been developed in the USA, whereas salt-tolerant landraces evolved in

Northern Africa where saline conditions are relatively frequent (Annicchiarico *et al.*, 2011).

The development of low-input farming systems has implications for breeding targets. These include: (i) breeding for adaptation to mixed lucerne–grass cultivation; (ii) adaptation to grazing, which is favoured by less erect growth habit and other characteristics which can conveniently be introgressed from *falcata* germplasm (Pecetti *et al.*, 2008); and (iii) high ability to compete with weeds, to reduce reliance on herbicides (Annicchiarico and Pecetti, 2010).

Breeding schemes

In most cases, lucerne breeding pools are composed of polycross progenies and new germplasm (landraces or cultivars). This plant material may be submitted to disease tests, selecting resistant plants for evaluation in a field nursery under spaced planting conditions or relatively dense conditions. In this design, the most heritable traits (plant height, lodging) and the traits that show a large within-family variation (digestibility, protein content, seed weight per inflorescence) are scored.

Breeding programmes frequently adopt a final stage selection for the best individuals, identifying the parents of future synthetic cultivars according to forage yield and quality traits of their half-sib progenies grown in dense, replicated micro-plots. Either the best parent plants or, less frequently, the best half-sib progenies (or the best plants within each progeny) are used to produce the first generation of a candidate cultivar (or possibly for entering a new cycle of recurrent selection). Multi-site trials can be used for testing the candidate cultivar or, when more than one candidate cultivar is available, for selecting one for registration in a national list of cultivars.

Up to now, the use of molecular markers in breeding programmes has been very limited. However, some results and prospects show that molecular tools, including genomic selection, should soon contribute to the genetic progress (Annicchiarico *et al.*, 2015).

Agronomical Role and Environmental Impacts of Lucerne

Beneficial role of lucerne in crop rotations

The benefits of lucerne in crop rotations arise from the ability to improve soil fertility and soil structure and to limit weed development in subsequent crops. Lucerne accumulates large amounts of N, commonly 300–400 kg/ha/year (Kelner *et al.*, 1997; Angus and Peoples, 2012). Up to 165 kg/ha of N are accumulated in the crown and roots (Rasse *et al.*, 1999; Justes *et al.*, 2001), which is available to subsequent crops. The N fertilizer replacement value of lucerne for subsequent crops is generally estimated at 100–200 kg/ha (Baldock *et al.*, 1981; Bruulsema and Christie, 1987; Hesterman *et al.*, 1987; Ballesta and Lloveras, 2010). A significant residual N effect of lucerne is also observed in the second cereal cropping year (Cela *et al.*, 2011; Vertès *et al.*, 2015).

Lucerne N rhizodeposition has been estimated to account for 3–5% of fixed N, a value which appears to be lower than for several other legumes (Brophy and Heichel, 1989; Lory *et al.*, 1992). Rhizodeposition is particularly low during the first year of lucerne cultivation (Heichel and Henjum, 1991). Lucerne rhizodeposition appears to be more related to changes in plant density and turnover of fine roots than to turnover of nodules (which are indeterminate) or to root exudation (Brophy and Heichel, 1989; Dubach and Russelle, 1994; Louarn *et al.*, 2015). Therefore, rhizodeposition during the growth phase appears to have a limited contribution to the residual N effects of this species, and the low values account for the low N transfer to grasses.

Approximately 25–35% of the crop residue is mineralized during the first year following the crop destruction (Angus *et al.*, 2006). The relatively slow initial decomposition rate of taproot and other thick roots probably explains the low initial mineralization rate of lucerne residues, along with the long overall duration of N release spanning several years. Crop destruction during the autumn is more favourable for mineral N release to a subsequent spring crop than the destruction during late winter, due to the longer period of N mineralization before establishment of the spring crop (Angus *et al.*, 2000).

In rotations, lucerne has a positive effect on subsequent crops through its capacity to improve soil structure and soil permeability. However, the ability of lucerne to take up water from deep in the subsoil through its extensive root system may lead to water deficit of the subsequent crop during its early growth under limited rainfall (Angus *et al.*, 2000).

Effects of lucerne on the environment

Lucerne can take up nitrate from deep soil layers (Blumenthal and Russelle, 1996). The risk of nitrate leaching below the lucerne crop is generally very low, even where manure is applied (Thiébeau *et al.*, 2004). Lucerne is considered an efficient forage species for nitrate-enriched soils (Russelle *et al.*, 2007). Emissions of nitrous oxide (N_2O) have been observed in the range 0.67–1.45 kg of N_2O-N/ha/year (Rochette *et al.*, 2004), which is intermediate between the lower emission rates of unfertilized grass and the higher emission rates of well-fertilized crops. However, higher N_2O emissions have been reported in succeeding crops (Wagner-Riddle and Thurtell, 1998). Lucerne crops accumulate significant amounts of C in the soil (Mortenson *et al.*, 2004) contributing to mitigation of C emissions.

Biodiversity (insects, birds, small mammals)

Lucerne is recognized as a key habitat for many species in mixed farming systems. In France, 40 insect species have been reported in lucerne (Raynal *et al.*, 1989) as potential pests for forage or seed production, but little is known about effects on lucerne production in natural conditions where biological interactions may regulate their abundance. A recent study in western France (Long Term Ecological Research (LTER) network, 'Zone Atelier Plaine et Val de Sèvre') identified more than 30 wild bee species in flowering lucerne crops, against ten concurrently found in sunflower crops (Rollin *et al.*, 2013).

Lucerne crops are also important habitats for other important taxa such as grasshoppers (Badenhausser *et al.*, 2012) and small mammals (common vole and mouse species) that use lucerne for overwintering and reproduction (Inchausti *et al.*, 2009). The abundance of these prey species drives the population dynamics of their predators at the landscape scale. An increase in the area of lucerne benefits skylarks (Kragten *et al.*, 2008), ortolan bunting (Morelli, 2012) and top predators, such as raptors (e.g. Montagu's harrier) (Salamolard *et al.*, 2000) or the little bustard (Bretagnolle *et al.*, 2011), which are birds of high conservation value. Some agri-environmental schemes support lucerne production (Berthet *et al.*, 2012). While butterfly species richness per field was 5.6 species in conventional lucerne fields in eastern France, it reached 8.8 species in lucerne managed to favour butterflies (Thiébeau *et al.*, 2010). Grasshopper densities in agri-environment scheme (AES) lucerne fields can be fourfold higher than in conventional fields (Fig. 11.6). The management of lucerne fields at the local and landscape scales is critical for both the maintenance of ecosystem services, such as those depending on functional biodiversity, and the conservation of threatened species.

Weeds

Weeds can be a problem in lucerne, particularly at establishment but also after each cutting. Approved herbicides are available. The introduction of lucerne into

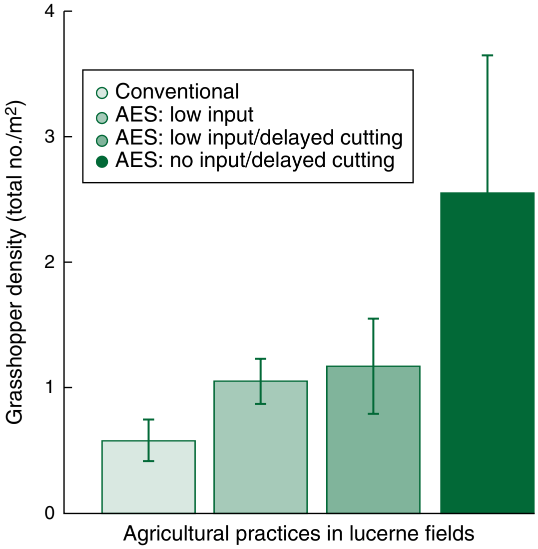

Fig. 11.6. Grasshopper density (all species cumulated) in conventional and agri-environment scheme (AES) lucerne fields (total number/m² ± standard error) in the Long Term Ecological Research (LTER) network 'Zone Atelier Plaine et Val de Sèvre'.

the rotation induces a change in the weed flora, with less climbing and erect annual dicots and more perennial dicots and annual rosette dicots. Therefore, including lucerne in rotations can reduce the risk of weeds affecting subsequent annual crops. Lucerne–grass mixtures can be used to reduce the risk of weed problems. From a breeding perspective, competitive ability against weeds is correlated with yield potential (Annicchiarico and Pecetti, 2010). Using mixtures of lucerne and annual legumes is also a way to decrease the development of weeds in the establishment year of lucerne while increasing forage production (see Chapter 12, this volume).

Harvest

Grazing

Grazing is not popular in Europe but is common in North and South America. It is the cheapest way to harvest forage. Rotational grazing is generally more convenient than continuous grazing, and should be limited to a few days, to reduce damage to new stems. Grazing-tolerant cultivars are required to maintain satisfactory persistence. The soil should be dry enough to prevent poaching which may cause serious damage to the plants. The grazing interval should be at least 35 days to enable the recovery of root reserves. In the south of France, autumn regrowth provides a high-quality forage that is utilized by sheep or goats. Breeding and selection increases grazing tolerance, allowing continuous grazing for cattle and sheep (Annicchiarico *et al*., 2010).

In some conditions (wet forage, high protein content, animals not accustomed to lucerne), foaming occurs in the rumen and may cause animal death, and this is a major disadvantage for many farmers. However, several management practices can minimize these risks: (i) grazing of Lucerne–grass mixture; (ii) no grazing in the early morning when the plants are still wet; and (iii) the use of anti-foaming agents.

Silage and hay

The choice of the cutting schedule is critical for yield, quality and persistency. Generally, the first cut of the year is conducted at budding stage and followed by cuts at 5- to 8-week intervals to maximize yield, give satisfactory nutritive value and support persistence. In Western Europe, 1–3 days of wilting are needed to make silage, 2–4 days to store in wrapped bales (about 40–50% moisture when the forage is wrapped) and 3–6 days to make hay (below 20% moisture). Silage is generally convenient for the first cut, when the quantity of forage is high enough to make a silo and the weather is not dry or warm enough for natural drying. Because of the high protein content, low sugar content and high buffering capacity, silage requires pre-wilting of the forage so that it is ensiled at a minimum of 35% dry matter. The sugar content affects preservation. It is higher at the budding stage than at flowering stage (6–10% compared with less than 5%) and at the end of the day than in the morning. Rapid wilting limits respiration and sugar losses. If the dry matter content of lucerne is lower than 35%, silage making requires the addition of either preservatives, other sources of sugar (e.g. a sugar-rich forage grass or molasses) or dry components such as dried sugarbeet pulp.

Wrapped bales are also used to make silage. Two conditions are needed to limit the development of butyric microorganisms that represent the main risk for preservation in wrapped bales: (i) no soil in the bales (obtained by a harvest height of at least 6–8 cm); and (ii) a dry matter content of 50–60%. The bale density must reach about 200 kg of dry matter/m^3. Depending on the water content of the forage in the bales, nutritive value of wrapped bales is higher than hay and may be similar to conventional silage.

Hay making is a traditional way to conserve lucerne, but skill is required to avoid field losses that can reach as high as 30%. Leaves dry quicker than stems and the nutritional composition of hay drops if leaves are lost during hay making. In humid environments, a morning mowing is recommended to benefit from the whole first day and increased drying rate. Roll conditioners crush the stems and enable faster and better synchronized drying of stems and leaves. Tedding and raking must be confined to early in the morning when the forage is still wet with dew to reduce leaf losses. All these methods still present a risk of low-quality forage and are time-consuming. Barn-drying has proved to be efficient but requires specific investment. Briefly, pre-wilted forage (60–65% of dry matter) is stored in a chamber and warm air is blown in and progressively dries it. The air may be heated using solar energy absorbed by the roof. A high-quality hay is obtained. For dehydration, factories establish contracts with lucerne growers and organize cutting and dehydration schedules. The stage of plant development, the distance from field to factory and the age of lucerne field are taken into account. Intervals between cuts are 40–50 days, depending on crop growth and the objectives of production (high protein and energy contents or high fibre content). During the lucerne harvest period (April–October), the factory works round the clock, while other crops or by-products are dehydrated in the other seasons. Thirty years ago, lucerne forage was delivered to the factory soon after mowing and was dehydrated at 600–800°C. In order to limit energy consumption, forage is now pre-wilted in the field before dehydration, and the drying temperature is close to 250°C, which is sufficient to produce a Maillard reaction between sugars and proteins, thereby limiting the protein degradability in the rumen and increasing the protein value of the crop.

Lucerne in Farming Systems

In mixed animal–crop production systems, lucerne or lucerne–grass mixtures are cultivated in rotation with annual crops devoted to animal nutrition (maize, cereals) and possibly with annual cash crops. Lucerne cropping is also introduced into annual cropping systems on stock-less farms and is traded as hay. Traditionally, these exchanges occur at a local scale between farmers. They are currently emerging at a larger regional scale, with the involvement of brokers such as cooperatives. Trade also occurs at the intercontinental level. Some countries such as China and Saudi Arabia import large quantities of compressed lucerne hay from California to support livestock production. To our knowledge, European producers of lucerne are not present in this international market of lucerne hay.

Feeding Value for Ruminants and Monogastrics

Ruminants

Lucerne is of high interest for ruminant feeding because of its high dry matter yield, protein and calcium contents, palatability and high level of intake. It has also a well-balanced amino-acid profile and provides higher amounts of minerals and vitamins than other forages. It is a flexible forage resource that can be grazed, fed as green forage, offered as hay or silage, or given as dehydrated roughage (Baumont *et al.*, 2014).

For dairy cattle, grazing can support up to 25 kg milk/day from an intake of 20 kg dry matter/day saving 1 kg soybean meal/day (Heuzé *et al.*, 2013). Given as fresh forage or as silage, it can replace up to 50% of a maize silage diet, enriching the diet in protein and minerals, avoiding metabolic disorders and reducing the use of concentrate feeds. Hay feeding alone supports 27 kg milk/day with up to 45 kg milk/day produced when it is supplemented with concentrate feed. Dehydrated lucerne can partially replace protein-rich concentrates in dairy cow diets, allowing high levels of production. In beef production, grazing needs supplementation with either grass hay (4–8 kg/day) or cereals (2–5 kg/day) to support high growth rates (up to 1.8 kg/day). Lucerne can also be used for feeding small ruminants such as sheep and goats, for either milk or meat production. High-quality lucerne hay and pellets are well suited for high-production animals while lucerne silage could be offered to lower-requirement animals.

The main difficulties for the farmers – and challenges for the future – are: (i) to protect lucerne from over-grazing; (ii) to get the best compromise between dry matter yield and quality; and (iii) to limit the high protein degradation rate.

The water-soluble carbohydrate:protein ratio is higher in lucerne–grass mixtures than in pure lucerne (da Silva *et al.*, 2013), and this increases the utilization of the protein (N) component. Combining lucerne with some grasses is generally a good approach to utilization.

Pigs and poultry

For monogastric feeding, lucerne is generally incorporated at a low percentage of the diet (Heuzé *et al.*, 2013). Its fibre content is high and limits animal growth rate. Its protein and also its mineral contents are valuable. The saponins have an anti-cholesterolemic effect and may reduce animal growth rate, even though a positive effect has been reported on the reduction of cholesterol content of animal products (Ostrowski-Meissner *et al.*, 1995). Carotenoids have a positive impact on the pigmentation of eggs and body lipids of poultry. Finally, the proportion of lucerne introduced in the diets of pigs or poultry is usually lower than 10–15% and is mainly composed of dehydrated products. For rabbits, the inclusion of lucerne is much more important. A rate of 40–60% of lucerne in the diet, as hay or pellets, is frequently recommended.

Novel and Non-food Use

Certain concentrated lucerne components are useful for animal health or animal quality products, human health, cosmetology, energy production and pet health.

Protein concentrates that are also rich in minerals and vitamins are produced from lucerne juice obtained after pressing and precipitation. They are distributed to fight against malnutrition in Africa and South America but could also be used for people suffering from protein deficiency. They have obtained the 'Novel food' label from the European Food Security Agency in 2009 as they may have the beneficial effects of ten out of 16 classes of food supplements. For ruminant production, the omega-3 fatty acids in lucerne could be used to improve the quality of animal production (milk and meat). The saponins that are naturally present can be used to reduce methane production in cattle (Beauchemin *et al.*, 2009; Malik and Singhal, 2009). Minerals and vitamins of lucerne can also be used for cosmetics and skincare. Research is being carried out to define dietary products to reduce or prevent obesity of companion animals.

Lucerne may also be used for energy production because of its high biomass production and its low N fertilization requirement. Energy production is based on the exploitation of cell wall polysaccharides, but a low N content is preferred to avoid greenhouse gas emissions. Integrated or cascade uses start with protein extraction for animal feeding or human supplement and then the polysaccharide residue is used as a source of biomass energy. In such a system, labour costs might be reduced because a longer regrowth period and lower plant density could be used to combine high yield with limited senescence of leaves (Lamb *et al.*, 2003). Specific cultivars, with an erect growth habit, thick stems and resistance to lodging, would be appropriate for this type of use (Lamb *et al.*, 2007).

Seed Production

Lucerne seed is mainly produced in the USA, Canada, Australia and Europe (France, Italy, Spain, Hungary and Serbia) (Boelt *et al.*, 2015). The favourable regions are characterized by a deep soil with high water reserves combined with summers that are warm and dry to ensure optimal seed maturation and harvest. Sowing density is lower than for forage production (4 kg of seed/ha) and rows are wider (around 0.35 m). Usually, the stands are clipped early in spring, so that lodging risk is reduced and flowering date coincides with bee activity that is further enhanced by dry conditions in late spring or early summer. Insecticide is often needed to avoid seed losses. Optimal management of lucerne seed production crops resulted in an increase in seed production from 200 kg/ha to 500 kg/ha in France in the past 30 years (Hacquet and Karagic, 2014).

Seed production has always been an important aspect of lucerne cultivation. In the past, seed exchanges or marketing were observed within a region, a country or overseas without strict control of the origin of the cultivar or the population (Julier *et al.*, 1996). Nowadays, seed yield influences seed prices and the commercial success of a cultivar is influenced by seed price, so a cultivar that is very good for forage production but poor for seed production is usually not available to the farmers. A significant international market for seed exists, with world trade dominated by exports from North America and Australia (Le Buanec, 1997; Huyghe, 2005).

Outlook

Lucerne has many advantages as a source of forage for animal feeding. Its high forage production and high protein content are combined with low N fertilization requirements, adequate persistence and beneficial agronomical effects on the following crop. Recent scientific studies have confirmed the renowned positive environmental impact of lucerne cropping. Actions are required to safeguard the cultivation of lucerne and boost its positive effects for European agriculture.

The Common Agricultural Policy in 2013 established that member states devoted 2% of Single Farm Payments to revive the production of protein-rich feed crops. To be efficient, this protein plan requires: (i) research and development to increase forage yield; (ii) development of processes for the medium scale; (iii) encouragement and support for the establishment of contracts between lucerne producers and users; (iv) information and extension; (v) development of programmes for livestock farmers, aimed at promoting multifunctional forage systems; and (vi) economic support to compensate for the lower financial returns for lucerne related to environmental benefits.

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