WP2 – Cropping possibilities

Task 2.2. Non-food energy crops rotation possibilities

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Lately conventional agricultural systems have increased their dependence upon external inputs, mainly on fertilizers and pesticides. The increased dependence constitute a challenge to the long-term productivity and sustainability of non-food crop and/or food crop systems because of environmental and logistics constrains. The importance of crop rotation, however, has been long recognized as an alternative system that can reduce agriculture's dependence on external inputs through internal nutrient recycling, maintenance of the long-term productivity of the land, avoidance of accumulation of diseases and pests associated with mono-cropping, and increased crop yields, (Gebremedhin and Schwab, 1998; Peel, 1998; Krupinsky et al., 2002). Crop rotation also can help to reduce soil erosion, improve soil structure, enhance permeability, increase biological activity, increase water and nutrient storage capacity, and increase the amount of organic matter in soils (Gebremedhin and Schwab, 1998; Peel, 1998).

The aforementioned beneficial effects can be further improved by combining crop rotations with cover crops and reduced or no-tillage practices (Gebremedhin and Schwab, 1998; Peel, 1998; Zenter et al., 2002). Moreover, combining crop rotation and pesticides is an effective way of reducing pest populations. Fallowing is also used in combination with rotation systems to enhance their beneficial effects, especially in dryland areas where there are few alternative crops to choose (Gebremedhin and Schwab, 1998). However, barriers that would stop farmers for adopting crop rotation systems are the need for diversified farm activities, and information, as well as more diversified equipments and storage facilities. Also because the management skills and required knowledge are higher (Ikerd, 1991; Peel, 1998). These barriers may be even more prominent in the case of new promising non-food energy crops.

Crop rotations are characterized by growing a wide variety of crops in a sequential system on a given cultivated land and by the associated management practices. Rotation plans are usually built around one or two leading crops, followed by one or more legumes and/or other crops. It is important, however, to include legumes in the rotation as they fix nitrogen, contribute to soil structure, to erosion control, to forage production, and cash hay and seed production.

Although various cropping systems can be technically feasible, there is no one right rotation system and a decision criteria is required to chose the best one that would fit to the specific conditions of a site [e.g. soil quality and fertility, environmental characteristics and/or profitability (Gebremedhin and Schwab, 1998; Peel, 1998)]. Therefore, rotation systems should be tailored to suit a particular farm or group of farms, and that involves many variables. For example, from the biological point of view the sequence of crops in rotation affect the availability and use of water and nutrients and consequently, crop yields. Therefore the criteria for selecting a crop rotation system could be based on the optimization of the use of such soil resources that usually are the two most limiting factors for crop production. In that case, crops that deplete soil resources should be alternated with crops that replenish, to some extent, soil resources.

Rooting depth and time to maturity are also important factors that should be considered when planning a sequence of crops in rotation. Deep rooted crops are best fitted to follow shallow rooted crops because the deep rooted crops can use the water and nutrients that moved to deep soil layers during the previous season, as in the case of small grain crops and sunflower or sorghum rotations. Medium or deep rooted crops appear to be better adapted to follow shallow rooted crops (Peel, 1998).

Other criteria to take in consideration when planning crop rotation systems are the environmental and economic conditions. Among the environmental factors, the climate and type of soils play an important role when choosing the species to be included in the rotation. The prevailing economic situation, availability of agricultural equipment, availability of economic resource, markets and laws are also important factors to consider when planning a rotation system.

When planning crop rotation systems, the current climate change scenario has to be considered too. As climate change will have an impact on land use and vegetation cover, it is predicted that the potential distribution of temperate oilseed, cereals, starch and solid biofuels will increase towards northern Europe by the 2080s, due to increasing in temperatures, and will decrease in southern Europe due to increasing drought (Tuck, et al., 2006). Therefore the tailored rotation systems for energy crops will have to adjust to the changing conditions and evolve continuously. For example, in the future hemp may not be appropriate in any rotation system in southern Europe as this crop is predicted to disappear from the region by 2080 (Tuck, et al., 2006). On the other hand, rotations with oilseeds, cereals, starch crops and biofuel crops could be intensified in northern Europe as they potentially will be more widely spread in this region.

In some cases, traditional food crops are used as dedicated crops with the advantage that they fit well into conventional crop rotations. This is the case, for example, of seed crops such as rapeseed and sunflower. Mostly, the production and rotation cycles of these crops, when produced for non-food purposes, does not differ much from the traditional practices and such crops can be included in rotations with traditional food crops. Therefore, at current and future scenarios, the description of their management in rotation can serve as a general guide for other crops of the same family. On the other hand, as the management of new energy crops is not well developed, research on rotations and crop sequences should be given high priority in order to evaluate their appropriateness and adaptability to fit specific conditions.

Among the large variety of annual, herbaceous perennial, and woody short rotation non-food crops that could be included in energy production systems, annual crops are, in fact, the ones which are intensively managed in rotation systems. Therefore the most prominent 4F annual crops selected in this review, based on their economic significance, geographical distribution, suitability to the climatic conditions, uses, and management practices are:

- Sweet and fiber sorghum,
- Flax,
- Rapeseed,
- Hemp,
- Sunflower and
- Ethiopian mustard

The information summarized in the following section focuses on the crop rotation possibilities of these 4F crops and their viability of been included in a rotation system alongside food crops based on their biological interactions and adaptability to climatic and geographical areas at a macro-regional level. Specific situations are, however, so different that generalized solutions are impossible. Therefore in the long-term the detailed information on management components (e.g. tillage, irrigation, harvest time, available equipment, etc.) and their interactions with the specific conditions of a site, agronomic potential, environmental impact and economics must be generated so dynamic farm-tailored crop rotations could be developed. The rotation possibilities utilizing perennial herbaceous species and woody crops is not considered here because of the long-term crop rotations required (between 10 to 20 years). Moreover, besides that planning such rotations are not attractive for farmers, the beneficial effects of long crop rotations may become insignificant, if there are any.

Sorghum (*Sorghum spp.*)

Sorghum management in rotation

In this section, sweet and fiber sorghum are discussed together because they belong to the same family and the suggested rotational practices may apply to both species. Sorghum is a highly productive C_4 plant of tropical origin and resistant to drought (Guiying et al., 2000). Therefore is best adapted to the Mediterranean climates of southern Europe and drier areas of central Europe. Several sorghum hybrids have been developed and improved throughout the years as dedicated crops for the production of lingocellulose, sugar and starch for the generation of bioenergy feedstock (Rooney et al., 2007).

A major advantage of sweet and fiber sorghum is that fit well into conventional crop rotations with food crops. It grows well in areas with a range of precipitations between 300 and 700 mm yr^{-1}, temperatures between 16 and 40 ^{o}C (Tuck et al., 2006). Sorghum can be successfully grown following maize or soybean crops. In New South Wales, Australia (Holland and Herridge, 1992) and in the Western Corn Belt, USA (Peterson and Varvel, 1989; Varvel and Wilhelm, 2003) it was found that soybean, cowpea and sunflower were the best predecessor crops in the rotation for sorghum. The increased yields of sorghum were attributed to the higher levels of nitrogen made available by the N-fixing legume or by the reduced N removal by sunflower. Legume-sorghum rotation studies indicated that legumes could contribute between 80 to 135 kg N ha^{-1} to sorghum (Blevins et al., 1990; Varvel and Wilhelm, 2003; Wortmann et al., 2007). Kaye et al. (2007), however, found that the fixed N by the preceding soybean accounted for 35% to 41% of the improved yields of sorghum, indicating that the increased availability of N is not the only reason for the increased yields. In fact, Bagayoko (2000) showed evidence that higher infections by arbuscular mycorrhizae of sorghum roots (compared to monoculture) grown in rotation with legumes contributed significantly to the increased yields. Unger (1984) suggested that including sunflower in the rotation allowed to a more complete and deeper depletion of soil moisture, even form deeper soil layers than sorghum water extraction layers, indicating that sunflower could be a more efficient user of the soil resources than sorghum due to its greater rooting zone. Then, the favorable effect of sunflower on sorghum yield could be partially explained by the different demands for nutrients. Sunflower, for example, takes up less phosphate from the soil than sorghum (Sauerborn et al., 2000).

Schlegel et al. (2002) showed that by including in rotation with wheat a crop with high water use efficiency, such as sorghum, the entire cropping system water use efficiency was enhanced, especially when the frequency of sorghum in the rotation was increased. The increased water use efficiency of the system was mainly due to the higher yields of the crops in rotation than in monoculture. Moroke et al. (2005) showed evidence that sorghum extracted water mainly from 1.0 to 1.8 m depth, in correspondence to the zones where most of the residual water was accumulated after the preceding cowpea. Therefore, such stratified water uptake may account for the increased water use efficiency of rotation systems that include sorghum.

Sweet and fiber sorghum are susceptible to a number of diseases including anthracnose (red stalk rot), fusarium, and maize dwarf mosaic. Since no fungicides are labeled for sorghum, these diseases could be controlled, to a limited degree, by using resistant varieties and by crop rotations with sunflower, cowpea, maize or soybean.

It has been reported that sorghum has inhibitory effects on weeds and following crops, especially when is grown in rotation with wheat (Einhellig and Rasmussen, 1989; Roth et al., 2000; Funnell-Harris et al., 2008). Phytotoxic compounds in sorghum stalks and leaves, may contribute to this allelopathic effect. Moreover Funnell-Harris et al. (2008) demonstrated that different sorghum genotypes affect soil microorganism populations in different ways, which in turn have variable effects on subsequent crops.

Suggested rotations

As mentioned above one of the most limiting factors for crop growth in Mediterranean climates is the availability of water. Therefore, the following analysis on sorghum rotations alongside with food crops was based mainly on the crops' water use criteria and their biological interactions. The research works on sorghum rotations suggest that the two following rotations: i) wheat – maize – sunflower – sorghum – fallow; ii) legume (e.g. soybean or other legume, probably cowpea) – maize – sunflower – sorghum (Unger, 1984; Holland and Herridge, 1992; Peterson and Varvel, 1989; Norwood, 2000; Schlegel et al., 2002; Varvel and Wilhelm, 2003; Moroke et al., 2005; Wortmann et al., 2007;) are worth of considering for the southern parts of Europe (Table 1). Since there is a greater probability of soil moisture to accumulate after wheat (or a legume) due to its shallower root system, the additional moisture stored in the soils favors the growth of maize after wheat. With soil moisture likely to be somewhat depleted after maize, sunflower have shown a great potential to extract water and nutrients that have moved to depths beyond the reach of either maize or sorghum which favors sunflower after maize. Sorghum requires the least amount of available moisture to sustain its yield production potential. This suggests that sorghum following sunflower as the last crop of the rotation before seeding wheat or a fallow period would be the best choice.

This rotation offers the possibility of introducing soil conservation practices such as no-tillage (Norwood, 2000; Moroke et al., 2005). With the availability of herbicides for the no-tillage practice, maize can be planted directly into wheat stubble, sorghum into sunflower stubble and wheat into sorghum stubble. Care, however, should be taken in order to minimize the phytotoxic effect that sunflower stubble has over some crops such as sorghum (Batish et al., 2002). In addition, it should be considered the phytotoxic compounds that some sorghum genotypes produce and their inhibitory effects on wheat (Einhellig and Rasmussen, 1989; Roth et al., 2000; Funnell-Harris et al., 2008), so probably a fallow period would be the best choice after sorghum.

Including a legume such as soybean (Varvel and Wilhelm, 2003) at the begging of an alternative rotation scheme could be beneficial for the system because legumes drive rotation systems, improve soil conditions and fertility, which makes weeds easier to control. Depending on the objectives and particular conditions of a farm or group of farms, the aforementioned rotation systems could be adjusted accordingly. A shorter rotation system, although may pose some threats to the soil organic matter content, of wheat (legume) – sunflower – sorghum could also be implemented in warm and dry climates.

In the hypothetical scenario where the existing infrastructure and organization of a region may require that all the production should be exclusively dedicated to supply feedstock for the bioethanol industry, the crop components included in the rotation should have such potential. In that case, it will be necessary to consider carefully the characteristics of the species included in the rotation, their interactions, growing conditions, and adaptability to the prevailing climatic conditions. In an attempt to do a preliminary exercise on that direction, a maize – sugar beet (or wheat) – sorghum rotation is suggested for warm summer climates (Table. 2). Sugar beet could be introduced in a double cropping system with autumn sowing. Rhizoctonia (*Rhizoctonia solani*) is a major problem for sugar beet production but in general, cereals do not host rhizoctonia root rot fungus and can help to break the disease cycle when included in a rotation (Stojšin et al., 2005). There is, however, controversial information on the disease reduction effect of maize (Ithurrart et al., 2004). So growing maize as predecessor crop for sugar beet should be carefully monitored. On the other hand, the rapid growth and consequent rapid soil cover by maize and sorghum, favors their positioning in the rotation as a way to control and reduce annual and perennial weed populations which are a major and costly problem in sugar beet production (May, 2003). Moreover, water may accumulate in the soil due to the lower water requirements of sorghum, which favors the growing of maize after sorghum.

Sunflower (*Helianthus annuus*)

Sunflower management in rotation

Sunflower is a well-suited crop for central and southern European regions as it can be grown within a range of 350 to 1500 mm yr^{-1} of precipitation, 15 to 39 ^{o}C of temperature and a similar altitudinal range to sorghum, hemp and flax (Tuck et al., 2006).

Sunflower performs well in rotation with food crops such as maize, wheat, chickpea, fodder peas, common vetch, soybean and sorghum but should not be planted in the same field more than once every three to four years due to the risk of build up of diseases (Johnston et al., 2002; Dogan et al.2008). As a double crop after wheat, sunflower is a good choice as well as soybean in northern zones (Halvorson et al., 2000). Weed problems, especially during the early growth stages of sunflower (Halvorson et al., 1999; Johnston et al., 2002) can be reduced by rotations with cool-season crops (e.g. small grain cereals) together with no-tillage and enhanced competitiveness of the crop (e.g. higher density, narrower row spacing, delayed planting; Anderson, 2005). In a dryland rotation, sunflower added diversity to the traditional wheat-fallow system and improved the efficiency of the system in terms of more intensive cropping and more efficient use of the stored precipitation, in particular when combined with reduced or no-tillage (Halvorson et al., 1999).

Sunflower has a shorter cycle than most crops, so can be planted later or harvested earlier, helping to spread the workload (Halvorson et al., 1999). The deep rooting habit of sunflower allows it to perform well when planted following a shallower rooted crop such as cowpea, wheat or proso millet (Stone et al., 2002; Kansas State University, 2005; Moroke, 2005). Moreover, sunflower is an efficient crop at extracting soil water (Hatterndorf et al., 1988; Norwood, 1999; Norwood, 2000); therefore, the yield of subsequent crops could be reduced, especially in drier zones or years (Nielsen et al., 1999; Norwood, 2000). Even though many authors have indicated the effective depletion of soil water by sunflower, its effects on subsequent crops are still not fully understood (Norwood, 2000). To reduce the potential failure of a crop after sunflower, soil water conservations measures should be taken and drought tolerant crops should be grown after sunflower. Under wet conditions (normal rain distribution, irrigation), however, the effect of sunflower on the subsequent crops is not a factor. In fact, it was found that the yield of crops following sunflower were increased when the soil moisture was adequate (Robinson, 1966; Porter et al., 1997; Kansas State University, 2005).

Due to the reduced crop cover left by sunflower, the risk of soil erosion is increased especially in areas with fragile soils. Bowman et al. (2000) found that the low amounts of residue after sunflower and the tillage practice used to incorporate herbicides for sunflower production reduced the soil organic carbon and organic matter-carbon and the yield of the subsequent crop (wheat). Moreover, Write and Anderson (2000) indicated that the introduction of sunflower in a wheat – fallow rotation leads to soil structural degradation. Therefore, it is recommendable to consider a fall cover crop after sunflower and the use of no-tillage or reduced tillage practices to decrease soil erosion and evaporation losses (Johnston et al., 2002; Kansas State University, 2005). In central Queensland, Australia the combination of no-tillage and crop rotation (wheat-sunflower) resulted in decreased soil erosion problems associated with the monoculture cultivation of sunflower (Carroll et al., 1997).

Other investigations reported phytotoxic effects of sunflower residues on some summer crops and weeds. Batish et al. (2002), for example, indicated that the yield of sorghum, maize, pearl millet and cluster bean were reduced due to the phytotoxic phenolics released from decomposing sunflower residues.

Suggested rotations

The following crop rotations: i) wheat – maize – sunflower – sorghum – fallow; ii) legume (e.g. soybean or other legume, probably cowpea) – maize – sunflower – sorghum, may work well for sunflower as they do in the case of sorghum because both crops grow well within the same environmental (central and southern Europe) range and share the same food and non-food crop sequencing possibilities (Table 1). In addition, the interactions between plants and uptake patterns of soil resource may be similar as in the sorghum rotation. However, care should be taken with the phytotoxic effects of sunflower residues (Batish et al., 2002). The complete decomposition or removal of sunflower residues before seeding the following crop should be considered carefully. Care also has to be taken with the specific varieties and genotypes of sunflower included in the rotation as the traditional ones used for food production has a high iodine number in the oil (Johnston et al., 2002; Venendaal et al., 1997) which hampers the biodiesel quality and engine performance (Pereyra-Irujo et al., 2009).

In the hypothetical case that large areas could be dedicated exclusively to produce oilseed crops and they will supply the feedstock demanded by a growing bio-oil industry, several oil crops could be used for that purpose. In climates with high summer temperatures and dry periods, however, only few alternative crops could be included in such rotation systems. Therefore, the suggested rotation for hypothetical disease free areas could be soybean – Ethiopian mustard – sunflower (Table 2). The high protein-oilseed production potential of soybean, besides its nutritional contribution, warrants its inclusion in a bioenergy crop rotation system together with Ethiopian mustard and sunflower. The nitrogen fixed by the preceding soybean could be beneficial for Ethiopian mustard as it is for rapeseed. Besides that, Ethiopian mustard can add diversity to the rotation and improve the efficient utilization of soil resources (Singh and Kumar, 1999). Sunflower, as already mentioned is a deep-rooted crop and efficient user of soil resources, which favors its growth at the end of the rotation.

A major problem, however, with this rotation is that the three suggested species are carriers and somewhat susceptible to Sclerotinia (*Sclerotinia sclerotiorum*). The use of certified seeds, newly developed hybrids with moderate resistance, possible fungicides, no-tillage and cultural practices such as wider row spacing may, to some extent, help to control the disease (Sackston, 1983; Peel, 1998; Myers, 2002; Kansas State University, 2005). Besides that, the drier environmental conditions where this rotation probably will be implemented, also favors to the limited progression of the disease. The inclusion in the rotations of less susceptible oilseed species such as crambe (*Crambe abyssinicia*) may also help to keep low levels of sclerotinia infestation. The risk of the breakout of such diseases should be prevented by all available means possible, including the combined application of some or all the cultural and chemical practices available (some of them mentioned above) following a well suited integrated pest management program. However, when sclerotinia appears, rotations to non-susceptible crops such as wheat, maize, sorghum are necessary

(Kansas State University, 2005). Rotations to non-susceptible crops must be carefully considered since the fungus remains alive in the soil for many years, even in the absence of host crops (Robson et al. 2002; Kansas State University, 2005). Therefore, the development of a bio-oil industry based on an agricultural system that includes only this kind of oilseed crops in the rotation seems to be risky and costly. Such specialized rotations may not work well in the long-term without the inclusion of species that are immune to such diseases (small grains) even though they do not produce feedstock for bio-oil energy purposes.

Rapeseed (*Brassica napus.*)

Rapeseed management in rotation

Rapeseed is the most widely grown energy crop across Europe. It is mainly grown in temperate climates of central Europe and parts of southern and northern Europe. Winter rapeseed is the dominant oilseed crop in northern Europe, often grown in short rotations with food crops such as barley and wheat (Rathke et al., 2005). It grows in areas with a range of 400 to 1500 mm yr^{-1} of precipitation and 6 to 40 ^{o}C of temperature. Rapeseed can be grown from 0 to 800 m.a.s.l. (Tuck et al., 2006). The crop is consider a high input crop as it requires high N fertilization and has low resistance to pests (Venendaal et al., 1997).

The introduction of rapeseed into wheat or barley rotational systems is possible with positive effects on the cereal yields. The main effect of including rapeseed in a rotation is due to better management of weeds and diseases (e.g. septoria, tan spot, etc.). The reduction in cereal diseases arises because rapeseed is not a host of cereal diseases and thus their populations tend to decline (Canola council of Canada, 2009). Moreover, rapeseed roots produce particular chemicals that are beneficial for the control of certain cereal root diseases such as soil-borne fungi and *G. graminis* (Halbrendt, 1996; Kirkegaard and Sarwar 1998; Robson et al., 2002; Norton, 2003). The positive effects of rapeseed in rotation are also ascribed to its potential to improve the soil structure, which leads to increased nutrient and water uptake, by the following crop (Kirkegaard et al., 1994; Christen et al., 1999; Johnston et al., 2002). There is also evidence that after growing rapeseed, the nitrogen availability was increased for the subsequent crop (McEwen et al., 1990).

On the other hand, the yields of rapeseed improve when grown in rotation with cereals. The yield benefits are more consistent when rapeseed is grown in a 1-in-3 years or 1-in-4 years rotation. The longer the rotation, the lower the nitrogen fertilization costs and the lower the insect/pathogen pest infestations (Christen and Sieling, 1995; Morrall et al., 1999;

Cathcart et al., 2006). Moreover, the rotation of rapeseed with cereals makes the system more efficient in terms of water use due to the different rooting depths and lower water requirements of rapeseed than cereals (Canola council of Canada, 2009). Even though the yield of rapeseed is increased following a cereal crop, several investigations showed that rapeseed yields were even significantly higher after pea, probably due to the supplied nitrogen by the legume that is highly demanded by rapeseed (Christen and Sieling, 1995; Sieling et al. 1997; Rathke et al., 2005).

But the crop sequence of cereal - rapeseed is not always beneficial, as indicated by the similar yields of cereals and rapeseed grown in monoculture and in rotation (Angus et al., 1991; Kirkegaard et al., 1994; Arshad et al. 2002). Moreover, an Australian study found that different wheat varieties had variable degrees of phytotoxic effects on rapeseed germination and growth (Bruce et al. 1999). Growing rapeseed on its own stubble is not beneficial either, because the promoted build up of diseases and insects; the deleterious effects of the previous crops were seen even up to two year later (Sieling and Christen, 1997; Sieling et al. 1997). Yield reductions can also occur when rapeseed is grown on other crops stubble susceptible to the same pests such as flax, mustard, sweet clover, soybean, field beans, lentils and sunflower (Canola council of Canada, 2009). Rapeseed should not be grown in rotation with sugar beet because the associated problems with rapeseed volunteers and the risk of nematode infection (Christen et al., 1999).

Increasing the frequency of rapeseed in a rotation (as in short rotations) may negatively affect beneficial organism populations such as rhizobia and vesicular-arbuscular mycorrhizal fungi (VAM) and their symbiotic relationships with subsequent crops (Krupinsky et al., 2002; Canola council of Canada, 2009).

The risk of soil erosion increases after rapeseed due to its characteristic low residue production and faster decomposition than cereals residues leaving the soil surface without cover, especially when is followed by summer fallow (Canola council of Canada, 2009). The inclusion of a summer cover crop (legume) in the rotation may help to reduce problems related soil erosion.

Suggested rotations

The studies on rapeseed rotations suggest that the rapeseed – cereal (e.g. wheat, barley, oat) – cereal (legume) – rapeseed rotation could be an important option for temperate zones (Table 1; Kirkegaard et al., 1994; Halbrendt, 1996; Kirkegaard and Sarwar 1998; Johnston et al., 2002; Robson et al., 2002; Norton, 2003; Canola council of Canada, 2009). Since the root systems of both species are structurally different and rapeseed has lower water requirements than cereals (Canola council of Canada, 2009), such sequence seems highly effective in terms of utilization of soil resources. Moreover, rapeseed is a high input crop and the use of residual nutrients by a subsequent crop could improve its yield and the profitability of the system. Besides that, cereals and rapeseed do not have common diseases; therefore growing cereals before or after rapeseed favors the control of diseases in both crops (Morrall et al., 1999; Canola council of Canada, 2009). This crop rotation also favors the introduction of reduced tillage practices with their consequent beneficial agronomical and environmental effects (Johnston et al., 2002). The introduction of a legume into the rotation could further improve the performance of the system (Christen and Sieling, 1995; Sieling et al. 1997; Rathke et al., 2005); the suggested crop sequence could be pea – rapeseed – cereal – cereal or rapeseed – cereal – legume – cereal. Moreover, a summer cover or cash crop, in a double cropping system, may improve the profitability of the rotation.

A tentative rotational system that would exclusively provide feedstock for a bio-oil industry could be rapeseed – flax – safflower (Table 2). To reduce the potential phytotoxic effects of rapeseed over flax, it may be beneficial to spread uniformly the rapeseed residues or seed flax into untilled rapeseed stubble (Flax council of Canada, 1998). On the other hand, since rapeseed is a high input crop, the residual nutrients, especially phosphorus (Grant et al., 2004 and 2009), may favor the growth of flax after rapeseed. Relative to the other oilseed crops, flax has the shallowest root system (Campbell and Zentner, 1996; Campbell et al., 2007), therefore water and nutrients are likely to accumulate in deeper layers. Therefore, the deep rooting system of safflower (Wachsmann et al., 2008), grown after flax, may take advantage of the accumulated resources and fulfill its higher water requirements. The benefits of including safflower, albeit its low yields, in a rotation can extend to the improved infiltration rates due to its deep root system, control of weeds, spread workload and risk management (Wachsmann et al., 2008). However, this hypothetical rotation, as the previous one, should be carefully considered and its implementation would be limited to certain areas free of diseases such as *Sclerotinia spp.* and *Fusarium spp.* In addition to this, similar preventive measures should be taken in order to avoid the build up of diseases that are difficult control through crop rotations and pesticides. The current problems associated with such diseases suggest that effort should be put in the search and/or development of new alternative oilseed energy crops that are resistant to a wide range of pests and at the same time have a high bio-oil production potential if specialized crop rotation system are going to be established.

Flax (*Linum usitatissimum*)

Flax management in rotation

Flax is a temperate climate crop that grows well across most of Europe including Northern Scandinavia. The temperature range for flax growth varies from 4 to 32 ^{o}C, minimum annual precipitation is 250 mm and at the maximum altitude for its cultivation is 900 m a.s.l. (Tuck et al., 2006).

Although flax is an ancient crop, few studies have addressed the rotation effects. It is recommended that flax should be grown in 3-year rotations to avoid the build up of soil-borne and stubble borne diseases of flax (Flax council of Canada, 1998). In studies on the Canadian prairies, Campbell and Zentner (1996) and Campbell et al. (2007) found that compared to wheat, flax conserve soil NO_3 and water below 60 cm depth, probably due to its shallower rooting habit. Other studies suggested that growing flax after wheat may help to strengthen the symbiotic relation with mycorrhiza and uptake of phosphorous (Entz et al. 2004; Grant et al., 2004 and 2009; Johnston et al., 2005) but not after rapeseed which is a non-mycorrhizal crop.

It is reported that flax sometimes produces poor yields after rapeseed and mustard due to toxic compounds in rapeseed and mustard residues (Grant et al., 2004). This is more evident when the stubble of the previous *Brassica* crops are not well spread on the soil. Either it is not recommendable to grow flax after potato, legumes or sugar beets (Flax council of Canada, 1998) as the soil could be too loose leading to Rhizoctonia problems. However Johnston et al. (2005) reported an increase of 20% of flax yield when seeded on pea stubble.

Flax is a poor stubble producer, which in turns results in reduced soil organic carbon gains, dryer and warmer soil surfaces than under wheat stubble. Therefore, selection of drought tolerant crops following flax in hot and drought prone areas seems recommendable (Johnston et al., 2002, 2005; Campbell, 2005; Merrill et al. 2006). The flax council of Canada (1998) and Krupinsky et al. (2006) indicated that flax performs well after cereals, maize, legumes and alfalfa while wheat and barley performs well after flax. Although the incidence of leaf spot diseases were high and low in barley and wheat, respectively, after flax the yield of both cereals was higher than on continuous cereal systems suggesting that other factors occurring in the cropping sequence had major effects on yield than the degree of the disease infestation (Krupinsky et al., 2004).

Suggested rotations

Due to the limited information on rotation systems including flax, this preliminary analysis suggests that the rotation flax – wheat – legume (Table 1) could be beneficial because of the potential stratified utilization of soil resources (Campbell and Zentner, 1996; Flax council of Canada, 1998; Campbell et al., 2007; Grant et al., 2004 and 2009; Johnston et al., 2005). Since there is a greater probability of soil moisture and nitrogen to accumulate in deep soils after flax due to its shallower root system (Campbell and Zentner, 1996; Campbell et al., 2007), the additional soil resources stored in deeper layers favors wheat following flax. As mentioned above, the inclusion of legumes into a rotation is always beneficial as they may improve soil conditions and fertility. However more information is required in order to precisely determine the plant interrelations and their effects in crop rotations including flax.

Hemp (*Cannabis sativa*)

Hemp management in rotation

Hemp has a long history as a fibre crop, but the energy end use of hemp is relatively new. In view of a more economic 2nd generation bioethanol production, hemp could take a leading role because of its high cellulose content. For the energy purposes, harvesting the whole plant is required (Venendaal et al., 1997). Hemp is ideally suited to mild temperate climates, and is mostly grown in central Europe and in some areas of northern and southern Europe. Hemp can be grown in areas with precipitations over 600 mm yr^{-1}, temperatures between 5 and 28 ^{o}C and altitudes up to 950 m.a.s.l. (Tuck et al., 2006). The yield of hemp is affected by environmental conditions and agronomic practices (Struik et al. 2000). Hemp fibres can be used as straw and hurds material, and energy production, while the oils from hemp can be used for food, cosmetics or pharmaceutical purposes (Ranalli and Venturi, 2004).

Lately only few studies have dealt with rotation effects of hemp. As an annual crop, hemp fits well into crop rotation where it may serve to the control of pests, as it is not related to conventional food crop species (Venendaal et al., 1997, Ranalli, 1999; Deeley 2002). Moreover, the high planting density and rapid soil surface cover by hemp (Struik et al., 2000; Robson et al., 2002) may help to the control of weeds.

Other studies indicated that hemp could be used in rotation as a nematicide, especially with crops susceptible to nematode attacks such as potatoes, maize, peas, grains and pastures. The suggested bio-pesticide effect of hemp is based on the findings that only few nematodes infests its roots and hemp plant extracts produce potent nematicidal agents (McPartland and Glass, 2001; Robson et al., 2002). Moreover, Kok et al. (1994) found that hemp could suppress soil pathogens such as *Verticcilum dhaliae*. There is also evidence that hemp can deter insect attacks (Robson et al., 2002).

According to Grochs et al. (2000), who studied the effects of hemp in a rotation with wheat in the humid cool areas of Northeastern Spain, hemp is a good precedent crop for wheat probably because of the leaf cover left and the increased soil aggregate stability. Increased yields of wheat where obtained up to the second year after hemp and the beneficial effects disappeared in the third year after hemp. The high leaf turnover rate of hemp and the retting process of hemp stalks provide large inputs of organic matter (Van Der Werf et al., 1996; Robson et al., 2002) that could be beneficial for increased yield of following crops. The deep rooting ability of hemp and its soil structure building effect (Robson et al., 2002; Amaducci et al., 2008) could also be beneficial factors in rotations with shallower rooted crops such as wheat.

Suggested rotations

The almost complete lack of information on rotational effects of hemp suggests caution in establishing a reference rotation across different environments. The limited recent studies on hemp rotations, however, suggest that hemp – wheat rotation works well in temperate climates (Grochs et al., 2000), but longer rotations including other food and non-food crops (possibly legumes to ensure adequate nutrition) should be tested. In the past century, however, Somma (1923) reported various long rotations for hemp that were suitable to the agricultural practices of that time. For the southern Europe, he suggested a five-year rotation composed by hemp – clover – clover – winter cereal – alfalfa and for northern Europe a longer rotation was reported: hemp – flax/clover – clover – wheat – rye – oat – potato – rye. In a review on hemp agronomy Dempsey (1975) suggested a four-year rotation of clover – clover – maize or potatoes – hemp or a five year-rotation of hemp – cereal – clover – cereal – alfalfa for European and North American environments. However, no data for such rotation was provided.

Ethiopian mustard (*Brassica carinata*)

Ethiopian mustard in rotation

Ethiopian mustard, native to the Ethiopian highlands, is well adapted to high temperatures and low rainfall (Cardone et al., 2003). The better adaptability of Ethiopian mustard than rapeseed to sub-optimal growing conditions makes it a suitable oil crop for rotations under the Mediterranean climates of southern Europe (Cardone et al., 2003). Ethiopian mustard could be included in any of the potential rotations suggested in Table 1 with crops such as sorghum, wheat, maize or kenaf. However, information on the rotational effects of such crop combinations (or any other) is not available. Moreover, as mentioned before, Ethiopian mustard could be included in dedicated energy crop rotations (soybean – Ethiopian mustard – sunflower; Table 2). Ethiopian mustard can add diversity to Mediterranean dryland rotations. Moreover, the deeper root system of Ethiopian mustard than that of rapeseed (Singh and Kumar, 1999) may favor a more efficient utilization of soil nutrients and its taproot system may help to improve the subsoil physical characteristics. Furthermore, including Ethiopian mustard in a rotation may reduce the use of agrochemicals (e.g. pesticides, fertilizers; Singh and Kumar, 1999), and increase profits through its higher yield (in Mediterranean climates) as compared to rapeseed (Mazzoncini et al., 1999; Cardone et al., 2003). However, as also mentioned before, care has to be taken with problematic pests and diseases common to these crops

Conclusion

Even though the rotation systems for sorghum, sunflower and rapeseed have not been specifically developed for their non-food production purposes, the management practices and rotation cycles do not differ much from the traditional food cropping practices. Therefore, the rotational management practices described here can serve as a general guide and could be also applicable for other food and non-food crops of the same family. On the other hand, the rotational management of new energy crops such as flax and hemp is not well developed, therefore research on rotations possibilities and crop sequences should be given high priority.

In the southern parts of Europe the best rotation choice that would optimize the utilization of soil resources and fit the prevailing climatic conditions would be wheat (legume) – maize – sunflower – sorghum – fallow (Table 1). As for temperate climates (northern Europe) rapeseed – cereal (e.g. wheat, barley, oat) – cereal (legume) – rapeseed rotation would be the best choice (Table 1). Moreover, the preliminary information analyzed here suggests that a rotation including flax – wheat – legume could be also beneficial for these regions (Table 1).

The great potential of hemp to be included in crop rotations, as it is not related to conventional food or non-food crop species, should be further developed.

In the hypothetical scenario where all the crops included in a rotational system are dedicated to the production of feedstock for bioenergy purposes, the tentative suggested rotation systems are summarized in table 2.

Table 1. Climatic regions and rotation possibilities

Environmental zones	Suggested crop rotations
Nemoral	• Rapeseed – Cereal (wheat, barley, oat) – Cereal (legume) – Rapeseed
Continental	• Wheat (legume) – Maize – Sunflower – Sorghum – fallow • Flax – Wheat – Legume
Atlantic central	• Rapeseed – Cereal (wheat, barley, oat) – Cereal (legume) – Rapeseed • Flax – Wheat – Legume
Atlantic north	• Rapeseed – Cereal (wheat, barley, oat) – Cereal (legume) – Rapeseed • Flax – Wheat – Legume
Lusitanian	• Wheat (legume) – Maize – Sunflower – Sorghum – fallow • Rapeseed – Cereal (wheat, barley, oat) – Cereal (legume) – Rapeseed
Mediterranean North	• Wheat (legume) – Maize – Sunflower – Sorghum – fallow • Flax – Wheat – Legume
Mediterranean South	• Wheat (legume) – Maize – Sunflower – Sorghum – fallow • Flax – Wheat – Legume

Table 2. Climatic regions and rotation possibilities in an hypothetical scenario where all crops are exclusively dedicated to the production of feedstock for bioenergy purposes.

Environmental	Hypothetical suggested crop rotations	Feedstock

zones		supplied
Nemoral	• Rapeseed – Flax – Safflower	• Bio-oils
Continental	• Maize – Sugar beet – Sorghum • Rapeseed – Flax – Safflower	• Ethanol • Bio-oils
Atlantic central	• Rapeseed – Flax – Safflower	• Bio-oils
Atlantic north	• Rapeseed – Flax – Safflower	• Bio-oils
Lusitanian	• Maize – Sugar beet – Sorghum • Soybean – Ethiopian mustard – Sunflower • Rapeseed – Flax – Safflower	• Ethanol • Bio-oils • Bio-oils
Mediterranean North	• Maize – Sugar beet – Sorghum • Soybean – Ethiopian mustard – Sunflower • Rapeseed – Flax – Safflower	• Ethanol • Bio-oils • Bio-oils
Mediterranean South*	• Maize – Sugar beet – Sorghum • Soybean – Ethiopian mustard – Sunflower	• Ethanol • Bio-oils

* Some crops such as maize and sugar beet may require supplemental irrigation.

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