Feasibility of paper mulches in crop production: a review

Tapani Haapala[1], Pauliina Palonen[1], Antti Korpela[2] and Jukka Ahokas[1]

[1]University of Helsinki, Department of Agricultural Sciences, P.O. Box 62, FIN-00014 University of Helsinki, Finland

[2]VTT Technical Research Center of Finland, P.O. Box 1000, FI-02044 Helsinki, Finland

e-mail: tapani.haapala@helsinki.fi

Mulching has become an important practice in modern field production. Plastics are the most widespread mulching materials, and especially black polyethylene is used almost everywhere due to its low price and proved positive results in production. Together with its still growing popularity, there is increasing concern about the environmental effects of using such vast amounts of plastics in agriculture without solutions for sustainable and safe disposal of the material. There have been several attempts to try to find safe and environmentally friendly alternative materials to replace plastic mulches. The use of biodegradable films is increasing because they can be left safely in the field after harvesting, but they are not very durable and are much more expensive than plastics. Another alternative is paper. This article reviews the published research on paper mulches and discusses the opportunity that they offer for solving the problems of the immense use of plastics in agriculture and the associated environmental threat. Different mulching materials have been used for different agricultural and horticultural species in different climatic environments, and results vary according to the chosen approach, growing practices, conditions and species, so generalizations are hard to make. One advantage of paper mulches is that they do not create the disposal problems that plastic films always and partially degradable bio-films often do in long-term use. Paper mulches break down naturally after usage and incorporate into the soil. Laying paper mulches in large scale farming is a problem to be solved. The quality of the paper needs to be adapted or improved for mulching purposes, and its price needs to be more competitive with that of plastic mulches. The review shows that there is considerable potential for using paper mulches in agriculture and horticulture.

Key words: paper mulch, crop growth, yield, soil temperature, soil moisture

Introduction

Farmers and horticulturists use mulching as a method of improving the condition of agricultural soils by covering the soil surface with different kinds of materials. Improvement of the soil physical environment contributes to better plant production (Vandenberg and Tiessen 1972, Bot and Benites, 2005, Chakraborty et al. 2008). Covering the ground with mulch may add organic matter to the soil, reduce weed growth, and reduce or eliminate erosion (Bot and Benites 2005). In landscaping, several kinds of organic mulches are widely used to control weeds and to enhance plant health (Tiquia 2002).

While mulching with organic matter was already used in ancient agriculture, there is also a long history of lithic (stone) mulches. More than a thousand years ago, in both the Old and New Worlds, farmers used lithic materials to mulch their dryland fields to avoid drought and to improve crop yield. Stones, gravel, pebbles, volcanic ash and cinder as well as other lithic materials have been used. The method not only reduces evaporation but also decreases wind erosion and surface runoff from fields (Lightfoot 1996.).

In the 1920s, asphalt paper mulch was widely used for pineapple (*Ananas comosus* (L.) Merr.) production in the Hawaiian Islands to control weeds and to conserve soil moisture (Freeman 1929). Adoption of the new approach was very fast. Just a few years from the first experiments of using paper as mulch the method was commonly used in the region. The farmers used tarred paper saturated with asphalt, which prevented weed growth, absorbed warmth in the soil and reduced evaporation from the soil. The method provided an enormous saving in field labor and a significant reduction in the cost of pineapple production in Hawaii (Coulter 1934). In an island of such a small population, the extensive production of pineapples without the paper mulch innovation, using hand cultivation methods, would have been impossible (Wilson 1948).

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Although the history of mulching with organic materials has been very long and beneficial for plant production, plastic mulches have widely replaced them and are very common practice, e.g., in vegetable production (Jenni et al. 2004, Moreno and Moreno 2008). The use of plastics has dramatically increased and is still growing, especially in China where it is estimated that the annual use of plastics for mulching is some 700000 t (Espi et al. 2006). This review surveys the research on paper mulches and assesses the possibility for the use of paper materials to solve the problems of the immense use of plastics in agriculture and its environmental impact. In addition, we have reviewed the research conducted on several other mulch materials, in order to be able to compare the advantages and disadvantages of different mulch materials and to assess their potential in replacing plastic. An ideal mulch would be made of renewable material, biodegradable, durable, permeable to rain and irrigation water, suppress weed growth, and have a beneficial effect on soil temperature and moisture. Furthermore, it should be cost-effective and easily manageable, including laying it in the field.

Different mulching materials in agriculture

In modern crop production several materials may be used for mulching. Farmers and horticulturists may choose among crop residues, different kinds of plastics, biodegradable films or different kinds of paper mulches coated or non-coated with plastic or biodegradable films. The effects of mulch type on crop growth can vary due to different production practices, growing conditions, and crop species (Ashworth and Harrison 1983).

Crop residue and organic mulching

Crop residue mulching is a technique where the soil surface is covered by the organic residue of the previous crop (Erenstein 2002), such as straw, maize stalks, palm fronds or stubble of leafy organic material that may also be brought from elsewhere (Bot and Benites 2005). Organic mulches include woody materials such as bark or sawdust, and also compost that is increasingly available where municipalities have recycling systems for green waste (Merfield 2002).

Crop residue mulching has been considered to provide several advantages to crop production. It improves yield of crops including yam (*Dioscorea rotundata* Poir) (Olasantan 1999), wheat (*Triticum aestivum* L.) (Chakraborty et al. 2008), groundnut (*Arachis hypogaea* L.) (Ghosh et al. 2006) and cassava (*Manihot esculenta* Crantz) (Opara-Nadi and Lal 1987). The yield increase might be partly due to the weed-suppressing effect of the mulch (Campiglia et al. 2010), since organic mulch cover on the surface of soil prevents germination of weed seeds. However, mulch is not sufficient to control perennial weeds if the soil is not first free from them and the material fully hot composted so all seeds or propagules of weeds have been fully destroyed by the heat (Merfield 2002). This might be particularly a problem when using straw or weedy hay without composting, as it can introduce more or different weed seeds to the field (Munn 1992).

Mulching reduces unproductive evaporation from the soil surface, so more water is available for transpiration, which is of benefit in water-limited conditions and plant water status is maintained (Chakraborty et al. 2008). Organic mulch also reduces erosion by protecting the soil surface (Erenstein 2002) and reduces nutrient loss by runoff and leaching (Olasantan 1999).

Some researchers have inferred that in hot climates, decreased maximum soil temperature has been a component of increased growth and improved yield (Olasantan 1999). A seven-year organic mulch study in India showed that the superiority of organic mulching compared to black or transparent polythene mulch or bare ground was partly due to improved soil water and temperature conditions that resulted in improved flowering, pod production and yield of groundnut (Ghosh et al. 2006).

In many studies, a positive effect of organic mulches on plant growth and yield has been documented, but not always. Jessop and Stewart (1983) found significant depression of early growth of wheat both at low temperatures (+8 °C) when wheat and sorghum residues were used for mulching, and at high temperatures (+24 °C), when rape, sorghum, field pea and wheat residues were used for mulching. The mulches had an adverse effect on germination and reduced shoot lengths. The authors suggested that the residues caused a major phytotoxic effect during early growth of wheat. Similarly, rape (*Brassica napus* L.) residues possibly result in stunting of cereal plants caused by toxins from either the residue or its decomposition products (Horricks 1969). Furthermore, organic mulches may rob nitrogen from the soil as they are decomposed by microbes (Merfield 2002).

Plastic mulching

Plastic films can be made from various thermoplastic polymers using film extrusion processes. Polyethylenes (PE), which are the basic materials of plastic mulches, are formed of long branched chains of C_2H_4 units. By using different polymerization and film-forming techniques and additives, it is possible to manufacture polyethylenes and polyethylene films with a wide range of properties and appearances. PE-mulch films have high strength, flexibility, elasticity, and resistance against chemicals and biodegradation, so very thin PE films can be used for mulching, and mechanized laying is possible. PE-films are also efficient barriers to water and water vapour (Heinemeyer 2005).

A few years ago, mulch film was the second most important application of plastics in agriculture after plastic greenhouses or tunnels (Espi et al. 2006), and by 2009, global use of plastic for agriculture was about 2.8 million tonnes. Mulch is now the largest use of plastics in agriculture and the market is hugely growing especially in China, where more than half of the globally applied plastic mulch is used. Although the largest demand of plastics is in Asia, demand is expected to grow strongly in Latin America, North America, the Levant and the Middle East (Reynolds 2010).

The films can be colorless or pigmented, aluminized or white. The width is usually up to 3 m, thickness between 12 and 80 µm, and they are often made of low density polyethylene. The planned lifetime of mulch films is usually two to four months (Espi et al. 2006). Black polyethylene is the most widely used due to its excellent properties (Moreno and Moreno 2008). Polyethylene is light weight, inexpensive, durable and easy to handle.

Although the increasing use of plastic mulches has improved crop yields, it also has distinct drawbacks. A major problem is how to remove the polyethylene from the field and how completely it can be done (Salokangas 1973, Pessala and Hårdh, 1977, Jenni et al. 2004). Shogren and Hochmuth (2004) estimated the cost of removal and disposal of plastic mulch from the field at 250 $ ha^{-1} in 2004. It seems to be even more laborious to remove the polyethylene that has been used to coat paper mulch when the paper part of the mulch has degraded (Miles et al. 2005).

Another huge problem is disposal of the collected material, since it is non-biodegradable. The residues can contaminate the soil and pollute the environment, they may be put into landfills or buried in soil, and these methods are merely temporary rather than permanent solutions (Kyrikou 2007). If the mulches are burnt, it must be done at very high temperatures to avoid releasing toxic compounds such as PCBs (Merfield 2002). This obviously is not happening in most cases. There is increasing evidence that plastic mulches may also increase level of phthalic acid esters (PAEs) in agricultural soil with a possibility of contaminating it (Wang et al. 2013). For all these reasons, substitutes for black plastic are desirable.

Biodegradable films as mulching materials

Alternative solutions for the use of plastics have been developed. From early 1980s, one alternative product has been biodegradable plastic (Zhang et al. 2008). The raw materials have mainly been aliphatic polyesters and starch-polymer blends that are made from renewable non-oil resources (Halley 2001, Sarnacke and Wildes 2008). These innovations present an environmentally friendly solution to the increasing problem of plastic disposal (Scarascia-Mugnozza et al. 2004). Biodegradable mulch films decompose slowly under moist soil, so they can be tilled into the soil after the growing period. Otherwise, biodegradable mulch films resemble PE-mulch films, as they can be laid on the soil in a similar manner and with the same equipments as PE-mulch films (Sarnacke and Wildes 2008). Martin-Closas et al. (2008) have shown that the type of biodegradable plastic mulch they tested in Spain with organic tomato (*Lycopersicon esculentum* Mill.) production is a good alternative to black plastic.

However, there is a concern that not all of the used polymers are fully biodegradable. Some of them have synthetic polymer, either in the formulation or as co-extruded film, to improve performance (Halley 2001). Many of the polymers that have been claimed to be biodegradable need specific circumstances for their decomposition, and are actually bioerodable, hydrobiodegradable, photodegradable, controlled degradable or only partially biodegradable (Kyrikou 2007).

The biggest disadvantage of biodegradable mulch films is their price, which is 2 to 3 times higher for the farmers than that of PE-mulch films (Halley 2001, Sarnacke and Wildes 2008). Furthermore, they are not as durable as polyethylene and may crack already early in the growing season (Moreno and Moreno 2008). Although biodegradable mulches are under continuous product development, they still are not cost-effective when compared to the alternative materials (Greer and Dole 2003).

Use of paper mulches in agriculture

Paper mulches may offer a solution to the problem of disposal of plastic mulches, since they can decompose fully after use and be incorporated into the soil (Merfield 2002, Salokangas 1973).

Although paper mulches are cheaper than biodegradable mulches, they are more expensive than plastics, their life span is shorter and they may expand and contract in ways that cause problems to the crop plants (Salokangas 1973, Merfield 2002).

The results of Monks et al. (1997) and Coolong (2010) showed the potential of paper-based mulches for use in vegetable production systems. Ueno et al. (1999) further developed the method of using paper mulches together with direct seeding of rice (*Oryza sativa* L.). Heat-melting glue was used to adhere the sheets of non-woven mesh and recycled paper and to support the grains of rice in the holes so they could germinate and grow at planting density. In this way, the mulch can control weeds so that herbicides are not required, it saves labor, it does not require special equipment, and transplanting is not needed.

Materials used for paper mulches

The composition and structure of paper is very different than that of polymer films. In most cases, paper is made by compressing moist, wood-derived fibres together followed by drying, and the fibres are bound together by hydrogen bonds. The length and diameter of wood-derived papermaking fibres are around 1.0–3.0 mm and 0.009−0.030 mm, respectively. Chemical pulp fibres are made by dissolving lignin of wood in a cooking process, resulting in separation of fibres having very low lignin content. Mechanical pulp fibres are separated from wood by mechanical refining. The composition of mechanical fibres is very close to that of wood, containing around 40−45% cellulose, 25−35% hemicelluloses and 25−35% lignin. When moderate or high brightness is required, the fibres are chemically bleached.

Choosing most suitable qualities and composition of raw and manufactured materials for paper mulches may be a way of improving their functionality, durability and suitability for agricultural purposes. Paper is inherently porous and hygroscopic. Its properties and appearance can be influenced in many ways by different treatments such as calendaring and creping, and by different constituents such as mineral fillers, dry- and wet-strengthening agents, colorants and water repellents. Wood-derived fibres are biodegradable, allowing the farmers to plough the used paper into the soil. Compared to PE-films and biodegradable films, paper is less elastic unless it is treated in a special way, for example by creping. Unlike polymer films, paper is hygroscopic, expanding and shrinking with change in its moisture content (Hakkila 1998, Daene 2005).

Many different kinds of materials have been used for paper mulches (Table 1). Furthermore, several different kinds of coating material have been used for improving raw paper materials. Kraft paper has been the most commonly used, either as-is or as a raw material for paper mulch products. Brown kraft paper is made of unbleached softwood pulp from the kraft process. The weight of commercial brown kraft papers is normally 40–135 g m^{-2}. Due to its high strength, brown kraft paper is commonly used for packing and wrapping. Commercial mulch papers are available as uncolored and black colored. A German mulch paper, ECOKrepp, is creped in order to increase its elasticity.

Table 1. Different qualities of papers used for mulching

Reference	Brand of paper	Color	Type of paper mulch
Anderson et al. 1995	Planter's Paper, USA	black	kraft paper, 52 g m^{-2}
	Hortopaper	brown	heavy-duty paper, 321 g m^{-2}
	nr	brown	recycled kraft paper, 65 g m^{-2} + soybean oil
Anzalone et al. 2010	Saikraft©, Saica paper, Spain	brown	200 g m^{-2}, 185 µm
Brault et al. 2002a, b	nr	black	kraft paper, 83 g m^{-2} + latex both sides
	nr	beige	kraft paper, 83 g m^{-2} + latex both sides
	nr	beige	kraft paper, 83 g m^{-2} + + biodegradable underside
	nr	beige	kraft paper, 83 g m^{-2} + + biodegradable top side
	nr	beige	kraft paper, 83 g m^{-2} + + biodegradable double sided
Coolong 2010	nr	white	butcher paper, 65 g m^{-2}
	nr	brown	kraft paper, 81 g m^{-2}
	nr	brown	waxed paper, 49 g m^{-2}
	nr	white	kraft paper, 81 g m^{-2} + polyethylene film
Coulter 1934	nr	tarred	asphalt-saturated paper
Freeman 1929			
Grassbaugh et al. 2004	nr	white	shredded newspaper, a depth of 10 cm
Harrington and Bedford 2004	EcoCover, New Zealand	brown	shredded waste paper glued between two sheets of brown paper
Hochmuth and Hochmuth 1994	Cascades brown, Canada	brown	nr
	Cascades black, Canada	black	nr
	Planter´s paper, USA	black	nr
	Cascades paper 488, Canada	nr	nr
	Cascades paper 410, Canada	nr	nr
Jenni et al. 2004	Kraft paper, Cascades Multi-Pro Inc, Canada	pale	kraft paper, 83 g m^{-2} + coating
		pale/black	kraft paper, 83 g m^{-2}, one side black colored + 5 different coatings
Jeon et al. 2011	nr	white	10 µm paper + biodegradable plastic
	nr	black	10 µm paper + biodegradable plastic
Martin-Closas et al. 2008	Patria Kraft, Patria Papier, Austria	nr	90 g m^{-2}

Table 1 continues

Reference	Brand of paper	Color	Type of paper mulch
Matitschka 1996	Nieuwerk and Fisher, Germany	black	black coloured paper
Miles et al. 2005	nr	brown	kraft paper, 132 g m^{-2}
	nr	brown	kraft paper , 68 g m^{-2} + polyethylene coating
Monks et al. 1997	nr	light	shredded newspaper, 2.5 cm and 12.7 cm depth
	nr	light	chopped newspaper 2.5 cm and 7.6 cm depth
Munn 1992		light	shredded newspaper, 10-40 t ha^{-1}
Pessala & Hårdh 1997	Clupak paper	brown	70 g m^{-2} paper + paraffin oil
	Clupak paper	brown	75 g m^{-2} + clear polyethylene film (15 g m^{-2}) + paraffin oil
	Clupak paper	brown	80 g m^{-2} + clear polyethylene film (15 g m^{-2}) + paraffin oil
	Clupak paper	brown	100 g m^{-2} + clear polyethylene film (15 g m^{-2})
	Clupak paper	black	90 g m^{-2} + black polyethylene film (20 g m^{-2})
	Clupak paper	black	100 g m^{-2} + black polyethylene film (20 g m^{-2})
	Clupak paper	brown	100 g m^{-2} + bitumenized
	Crepe kraft paper	black	75/100 g m^{-2} + black polyethylene film (20 g m^{-2})
	Crepe kraft paper	brown	90 g m^{-2} + synthetic fibre
	MF-spinning paper	brown	65 g m^{-2} + paraffin oil
Radics and Bognar 2004	KRAFT R	beige	kraft paper, 70 g m^{-2}, recycled pure cellulose
Runham et al. 1998	nr	light	derived from recycle fibres
Sanchez et al. 2008	nr	light	shredded newspaper, 10-15 cm depth
	nr	light	sheets, five sheets
Shogren and David 2006	Brown kraft paper, Carter Paper and Packaging, USA	black	kraft paper, 49 g m^{-2} + carbon black and vegetable oil
		black	kraft paper, 65 g m^{-2} + carbon black and vegetable oil
Shogren and Hochmuth 2004	Brown kraft paper, Carter Paper and Packaging, USA	black	kraft paper, 65 g m^{-2} + linseed oil, carbon black and Co
		black	kraft paper, 65 g m^{-2} + linseed oil, carbon black, Co and preservatives
		black	kraft paper, 65 g m^{-2} + soybean oil, carbon black and Co
		black	kraft paper, 65 g m^{-2} + soybean oil, carbon black, Co and preservatives

nr = not reported

Degradability

Paper mulch is either fully or partially organic in cases when it is covered or treated with inorganic material. All papers meant for mulching which are not covered with polyethylene or some other non-degradable material are biodegradable, i.e., they decompose in the soil. Degradation occurs unevenly, with those parts that are covered by soil degrading first and those above the soil later. Quality and type of paper mulch naturally have a significant effect on degradability of the mulch and on the time it takes (Table 2.).

Sanchez et al. (2008) found that newspaper degraded the most rapidly, followed by shredded newspaper, and straw mulch was slowest in degradation. Uneven degradation of the newspaper mulches resulted in higher weed population in the experimental plots. The papers degraded primarily along the edges of the sheets, enabling weeds to grow where the sheets overlapped. When using recycled paper as mulch in direct seeding of rice, Ueno et al. (1999) found that it was degraded and indistinguishable in 40–50 days after seeding, but that was sufficient time that the density of weeds was low and their appearance was delayed.

An obvious disadvantage of most of the available paper mulches is their rapid degradation along the edges in contact with the soil. Hochmuth and Hochmuth (1994) found that the paper mulch they tested in Florida tended to tear from the edges and degraded too quickly, and in both experimental years one paper mulch was blown off most plots. Martin-Closas et al. (2008) also mentioned the degradation of buried edges of paper at the end of the cropping period but said that it would not have caused particular difficulties. Anzalone et al. (2010) noted the degradation of the aboveground portion of the biodegradable plastic in their tomato mulching experiments, whereas both paper and black plastic remained intact until the end of the cropping cycle. Nevertheless, the paper mulch was partially lifted by wind when the buried edges had degraded (Table 2).

There is still room for product development in paper industry. One direction might be strengthening paper with biodegradable, water-resistant layers. When paper is coated with a degradation-resistant material, such as biodegradable plastic film on the upper side only, it may allow the mulch to degrade within a single cropping season. Coolong (2010) observed that waxed, butcher, and kraft paper mulches degraded completely, but polyethylene-coated kraft paper mulch left a thin plastic film behind when the paper portion was completely degraded. Plastic mulch was intact after the experiment. Biodegradation may be slowed by placing the coated surface down, but this may cause another problem during rainy periods and the continuously moist surface of the mulch can encourage disease development (Brault et al. 2002b).

In some cases, oil coating has been seen as a solution to the fast degradability of paper mulches. Already in the 1960s, Salokangas (1973) used paraffin oil to impregnate clupak-paper mulch. The treatment increased thermal transmission capacity of the paper. Anderson et al. (1995) have shown that both unused and waste cooking oil significantly delayed both decomposition and loss of tensile strength in laboratory and greenhouse tests. Oil treatment also retarded decay of paper mulch at the soil line under field conditions. The authors suggested that microbial decay of the edges buried in soil is the primary reason for paper mulch failure and that oil may protect the paper itself from microbial attack.

Saturating paper mulch with vegetable oil significantly prolongs its usage time. Shogren and Hochmuth (2004) and Shogren and Rousseau (2005) found that paper mulch coated with vegetable oil lasted in good shape up to three months. Thereafter, a few cracks and holes developed in the coated paper mulch but these did not allow a noticeable amount of weeds to penetrate the mulch or detachment of the buried edge.

Paper coated with soy oil degraded faster than when coated with linseed oil (Shogren and Hochmuth 2004). The difference is thought to be due to the higher proportion of linolenic acid and cross-linking density of linseed oil. Nevertheless, both paper mulches lasted long enough for one crop cycle. Another explanation for slower degradation of oil-coated paper might be that the oil coating covers and fills the space between cellulose fibrils, allowing less surface area for growth of microorganisms (Shogren 1999).

There are some drawbacks to the use of oil coating to slow the degradability of paper, as the paper is more messy to handle and slower to lay (Shogren and Hochmuth 2004). Other researchers have found that oil treatment did not improve durability of paper mulches. Schonbeck and Evanylo (1998) found that oiled paper deteriorated especially quickly and tore extensively by thirty days after planting.

Overall, the degradability of paper mulches is a complex issue. The degradation process is strongly dependent on the quality of paper (Table 1), the quality of soil, and the weather conditions in the season of use.

Table 2. Durability and efficiency of paper mulches to control weeds on different crops

Reference	Type of paper mulch	Durability	Weed control
Anzalone et al. 2010	kraft paper (Saikraft©) 200 g m-², 185 µm	some wind damage	effective
Brault et al. 2002b	black kraft paper, 83 g m^{-2} + latex both sides		effective
	beige kraft paper, 83 g m^{-2} + latex both sides		moderate
	beige kraft paper, 83 g m^{-2} + biodegradable underside		moderate
	beige kraft paper, 83 g m^{-2} + biodegradable top side		poor
	beige kraft paper, 83 g m^{-2} + biodegradable both sides		moderate
Coulter 1934 Freeman 1929	asphalt-saturated paper	nr	effective
Grassbaugh et al. 2004	shredded newspaper, 10 cm depth	nr	moderate
Harrington and Bedford 2004	shredded paper glued between two sheets of brown paper	dislodged by wind at exposed sites	effective
Hochmuth and Hochmuth 1994	kraft paper with black pigment	blown off most plots	nr
Jenni et al. 2004	kraft paper, 83 g m^{-2}		
	P + coating, C1	nr	moderate
	P/B + coating, C2	nr	effective
	P/B + coating, C3	degraded fast	effective
	P/B + coating, C4	degraded fast	effective
	P/B + coating, C5	degraded fast	effective
	P/B + coating, C6	nr	effective
	P/B + coating, C7	nr	effective
	B/P + coating C5	nr	effective
	B/P + coating C6	nr	effective
Jeon et al. 2011	white=10 µm white paper + biodegradable plastic	nr	moderate
	black=10 µm black paper + biodegradable plastic	nr	effective
Martin-Closas et al. 2008	kraft paper (Patria Kraft) 90 g m^{-2}	degradation of buried edges at the end of cropping period	effective
Monks et al. 1997	shredded newspaper, 2.5 cm depth	nr	poor
	shredded newspaper, 12.7 cm depth	nr	effective

Table 2 continues

Reference	Type of paper mulch	Durability	Weed control
	chopped newspaper, 2.5 cm depth	nr	moderate
	chopped newspaper, 7.6 cm depth	nr	effective
Munn 1992	shredded newspaper, 15-22 cm depth	nr	moderate
Radics and Bognar 2004	kraft paper, 70 g m^{-2}, recycled pure cellulose	nr	effective
Runham et al. 1998	derived from recycle fibres	wind damage	moderate
Sanchez et al. 2008	chopped newspaper, 10-15 cm depth	nr	effective
	five sheets of newspaper	nr	moderate
Shogren & David 2006	30 lb brown kraft paper	nr	effective
	40 lb brown kraft paper	nr	efficient
Shogren & Hochmuth 2004	40 lb brown kraft paper + linseed oil + Co + carbon black	better than with soybean oil	effective
	40 lb brown kraft paper + linseed oil + Co + carbon black + preservat	better than with soybean oil	effective
	40 lb brown kraft paper + soybean oil + Co + carbon black	nr	effective
	40 lb brown kraft paper + soybean oil+ Co + carbon black , preservative	nr	effective
Ueno et al. 1999	mulch paper for direct seeding	lasted 40-50 days	moderate

weed control - effective, moderate, poor
nr = not reported,
P = pale, B = black
Co = cobalt octoate

Effect of paper mulches on soil conditions and plant growth

Paper mulches have been used for several horticultural crops including tomatoes, beans (*Phaseolus* sp. L.), beets (*Beta vulgaris* var. *cicla* L.*)*, peppers (*Capsicum annuum* L.), cabbage (*Brassica oleracea* var. *capitata* L.), sweet corn (*Zea mays* var. *saccarata* Koern.), cucumbers (*Cucumis sativus* L.) and muskmelons (*Cucumis melo* L.). The results have been very variable depending on the climatic environment, crop species, agricultural practices, and mulching materials.

Soil temperature

Crop species in the tropics and originally from the tropics require different soil temperature and other conditions for good growth than temperate crops. Mulch can modify soil temperature in those geographical regions where that is needed. In an environment that is not sufficiently warm for the growth of a warm-climate species, higher soil temperature can be beneficial (Abdul-Baki et al. 1992).

Paper mulches may lower soil temperature as compared to black plastic or bare soil (Table 3). In the UK, Runham et al. (1998) noticed that beneath the paper mulch, soil temperature was lower than in black polyethylene-covered or non-mulched plots. They attributed this effect to the lighter color of paper reflecting light that normally was absorbed by darker surfaces, either soil or black plastic film. Nevertheless, paper mulch tended to give more uniform temperature than the other mulch treatments.

Coolong (2010) grew summer squash (*Cucurbita pepo* L.) in Kentucky, USA using different mulching methods. Under the waxed paper mulch the average soil temperature was higher than when using butcher paper or kraft paper. However, under the black plastic mulch the soil temperature was significantly higher than under any paper mulch. In Manitoba, Canada, soil temperature under biodegradable mulch paper and brown kraft paper was lower than under commercial plastic mulch (perforated commercial plastic weed barrier, color not reported) or even bare soil (Zhang et al. 2008). In Finland, average soil temperature for pickling cucumber (*Cucumis sativus* L.) was lower under paper mulch than under clear polyethylene or bare soil (Pessala and Hårdh 1977).

Salokangas (1973) used different mulching methods to enhance earliness of pickling cucumbers in Finland. She found that paper was able to raise the temperature of soil in early summer but clear polyethylene increased the temperature most. Munn (1992) found that shredded newspaper and wheat straw provided a cooler and moister soil environment than bare soil under sweet corn (*Zea mays* L.), field corn (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.) and processing tomatoes in Wisconsin, USA. In New York, USA, during an especially cold and wet spring, paper mulch increased soil temperature which hastened early growth of potato (*Solanum tuberosum* L.), but during the other more normal years, there was no such difference between the mulching methods when papered plots were compared to cultivated plots (Hardenburg 1932).

In some experiments, the color of mulching paper has had an effect on the soil temperature. Schonbeck and Evanylo (1998) attributed the reduced daytime soil heating of black paper or kraft paper that was lighter-colored but fairly opaque to reflection of solar radiation. Coated brown kraft paper has been observed to lighten in color over the growing period leading to reduced soil warming later in the season (Shogren and David 2006).

Treating the paper with oil may affect its soil heating capacities. Oil-impregnated paper improved the transmission of thermal radiation, raising soil temperature and improving the earliness of the cucumber crop (Salokangas 1973). Anderson et al. (1995) also observed increased light transmission, when kraft paper was treated with oil. Consequently, soil temperature under oiled kraft paper mulch was higher compared to bare soil or unoiled paper, but not higher than under black polyethylene mulch. Similarly, Schonbeck and Evanylo (1998) noticed that oiled paper mulches increased soil temperature even more than plastics, but the effect decreased as decomposition and dust accumulation rendered the paper opaque.

Soil temperature is related to the geographic location where crop plants are grown. Numerous articles about mulching describe experiments and publish results that have only limited importance in other climatic regions. In some regions, where farmers need lower soil temperature for higher yield, while in others, higher soil temperatures are desirable. For example, for wheat in New Delhi in India, Chakraborty et al. (2008) found that increased soil temperature under mulch did not increase yield, and attributed this lack of effect to the already high soil temperature. Paper mulches may be more suitable for cool-season crops or mid-season production of warm-season crops because they lack the soil-heating capacity that is necessary for earliness (Jenni et al. 2004).

Table 3. Impact of paper mulch on soil temperature and water content at different locations

Country/location	Latitude	Color of paper mulch	Impact on soil temperature	Impact on soil water content	Reference
Hawaii, USA	19°–20° N	tarred	nr	increased	Freeman 1929
Kentucky, USA	37°58′ N	white	increased	nr	Coolong 2010
		brown	increased	nr	
West Virginia, USA	39°37′ N	light	decreased	increased	Monks et al. 1997
Ohio, USA	40°48′ N	light	decreased	nr	Munn 1992
MA, USA	41°34′ N	brown, oiled	increased	nr	Anderson et al. 1995
		brown	neutral	nr	
New York, USA	42°27′ N	light	increased	nr	Hardenburg 1932
Quebec, Canada	45°11′ N	pale	increased/neutral	increased/neutral	Jenni et al. 2004
		black/pale	increased/neutral	increased/neutral	
Hohenheim, Germany	48°42′ N	black	nr	increased	Matitschka 1996
Mepal, UK	52°24′ N	light	decreased	increased/neutral	Runham et al. 1998
Piikkio, Finland	60°25′ N	brown	increased/decreased	increased	Pessala and Hårdh 1997
		black	increased/decreased		

nr = not reported

Soil water content

Soil water content depends strongly not only on precipitation and irrigation, but also on temperature, evaporation and soil structure. Mulching can conserve soil moisture and modify its physical environment (Chakraborty et al. 2008, 2010). The positive effects of mulching on the soil water content are certainly dependent on the climate. In Finland where the climate is cool-temperate, only small differences in soil moisture developed under different kinds of paper mulches, clear polyethylene film or bare soil (Table 3) (Pessala and Hårdh 1977).

When there was no mulch on the soil in lettuce (*Lactuca sativa* L.) plots, it dried faster than when covered with black paper or plastic mulch (Matitschka 1996). In Canada, Zhang et al. (2008) determined that both a biodegradable mulch paper and brown kraft paper could keep the soil moister than commercial plastic mulch. In contrast, Jenni et al. (2004) showed that while paper mulches efficiently conserved soil moisture in lettuce crops during dry periods, polyethylene was even more effective.

Oil treatment of paper mulch may improve its capacity to conserve soil moisture. Untreated paper was more permeable to moisture than black plastic or oiled paper, but may have accelerated moisture losses later in the season due to rapid decomposition (Schonbeck and Evanylo 1998). The highest soil moisture levels when compared to plastic and paper mulches were observed under organic mulches (hay or compost) that allowed rainfall and overhead irrigation to penetrate but reduced evaporative losses. Similarly, Anderson el al. (1995) showed that oil-treated paper reduced water evaporation significantly more than untreated paper, and embossed black polyethylene was most efficient in reducing water evaporation.

Insect pests and diseases

Mulch cover can play a neutral role or reduce the risk of insect pest attack to crop plants by preventing direct movement of insects from soil to plants, but sometimes mulch may increase the risk of insect invasion. In Hawaii the use of asphalt paper as mulch in pineapple fields became very common in the 1920s because it was ideal in conserving moisture in soil and in weed control, but underneath it, insects and nematodes started to flourish, creating a serious problem (Freeman 1929). Crop rotation helped the situation considerably, but as it was rather expensive due to lowered total yield, farmers started to use soil fumigants (Wilson 1948).

There are not many published studies on the effects of paper mulching on insect pests. The reduction in number of insects early in the season may have contributed to plant survival by delaying the onset of viral infections and other diseases. When tomatoes were grown on black polyethylene-coated paper mulch there were fewer granulate cutworms (*Feltia subterranea* Fab.), and less injury of fruits in early spring (Price and Poe 1977). Later, when foliage shaded the mulch and temperatures became as low as those of the unmulched plots, there were no differences in cutworm activity.

Weeds

Weed control accounts for a major part of pre-harvest production cost. Weeding is usually done manually or mechanically in cases when no efficient post-emergent herbicides are available (Jenni et al. 2004) or farmers are not willing to use them. An advantage of using mulches is the fact that when mechanical or manual weeding is not needed, root damage of crop plants is minimized (Brault et al. 2002b).

In Hawaii, weed control in large pineapple fields was unmanageable before asphalt paper mulch was invented because manual cultivation required more manpower than was available. The problem was mostly solved by using mulch paper made of waste fibers from sugar factories (Wilson 1948).

In many studies paper mulches have been observed to be equally or more effective than black plastic mulch for weed control (Table 2). Coolong (2010) found that in the first year, butcher paper and polyethylene-coated kraft paper were equally effective in weed control as black plastic mulch. In the second year, black plastic mulch was better than the other mulches. He suggested that although paper mulches can be effective in preventing weed growth, their effectiveness depends on cropping conditions and the environment. In another study in four successive cropping seasons in the UK, paper mulches were shown to suppress weeds for the duration of cropping, a maximum of sixteen weeks (Runham et al. 1998). Only those weeds that grew through the planting holes caused more problems than in the case of plastic mulches.

Harrington and Bedford (2004) showed that mulch made of shredded waste paper glued between two sheets of brown paper was even better in preventing weed growth than black plastic, because the paper folded into the planting holes better than plastic, preventing weeds from establishing. However, according to Runham et al. (1998), weeds that grew through the planting holes of paper mulch caused more trouble than in the case of plastic mulches.

In a three-year trial in Zaragoza, Spain, paper mulch was even better in controlling weeds of tomatoes than black polyethylene or biodegradable plastic mulch (Table 2) (Anzalone et al. 2010). Most of the mulches controlled almost all different weed species, but only paper mulch could prevent growth of purple nutsedge (*Cyperus rotundus* L.). Shogren and Hochmuth (2004) also found that growth of nutsedge plants was not prevented by polyethylene mulch, but the weeds were not able to pierce the paper mulch, possibly because the cellulose fibers were more able than the polyethylene film to resist the sharp tips of the sedge shoots.

In some studies paper mulches have been found to be comparable to plastics in weed control. Radics and Bognar (2004) grew tomatoes and green beans in Hungary in two years when weather conditions were very different, one very dry and another very humid, and of the various mulch materials, paper and black plastic film were equally good at controlling weeds in both weather conditions. For tomato production, polyethylene, paper and biodegradable plastic mulch, were equally good in controlling weeds (Martin-Closas et al. 2008) .

The color of paper mulch may play an important role in controlling weeds. Jeon et al. (2011) showed that black paper mulch and black plastic mulch with hairy vetch alone were equally effective in controlling weeds in rice, but white paper mulch was not as good. Both polyethylene mulch and black-sided paper mulch equally effectively controlled weeds in experimental plots of lettuce (Jenni et al. 2004). Black paper mulch offered complete weed control, but under beige paper mulch weeds developed up to the two-true-leaf stage (Brault et al. 2002b).

Shogren and David (2006) suggested that paper mulches treated with polymerized vegetable oil would prevent weed growth. In their experiments, oil-treated paper mulch was equally good at preventing weed growth as newspaper covered with straw. Already in his earlier studies Shogren (1999) showed that coating paper mulches with vegetable oil resins extended their useful life to that needed for many crops to be ready for harvest. Kraft paper (65 g m^{-2}) alone and also treated with vegetable-based cooking oil for mulching tomato plots became extensively torn by midseason, allowing weed growth throughout the tomato plots (Schonbeck 1998). Both untreated and oiled kraft paper allowed enough light to penetrate that weed growth started beneath the mulches, and within four weeks after planting, the weeds generated enough pressure to tear the paper. Anderson et al. (1995) came to the conclusion that increased light penetration allowed weed growth beneath oiled paper mulches to exert pressure against the paper, causing the mulch to tear at almost the same time as untreated paper that failed due to decay at the soil line.

Yield

Mulching may increase yield and also improve yield quality, for example strawberry fruits remain clean as they are not in contact with soil. Particularly in conditions where nutrients and organic matter in soil are scarce, organic mulch application has increased the yield and reduced its yearly variation (Cadavid 1998). Increase of yield in some mulching studies has been attributed to higher soil temperature combined with an early planting date (Abdul-Baki et al. 1992). Mulching promoted shoot biomass accumulation of plants, leading them to entering the maturation phase sooner and remaining in it longer, improving the transport of assimilate from vegetative to reproductive organs and resulting in higher yield (Li et al. 1999). The reflective plastic used for strawberries in a greenhouse may also have increased their photosynthetic activity, resulting in increased yield (Al Khatib et al. 2001).

Mulch cover has resulted in increased yield of vegetables such as pickling cucumbers comparing to bare ground, hand weeded or non-weeded plot (Table 4) (Pessala and Hårdh 1977). Head lettuce yield was significantly higher when paper mulch was used in a warm and dry season (Brault et al., 2002a). Kraft paper, oiled kraft paper and commercially available black paper mulch improved total yields of tomato over the unmulched treatment, but to a lesser extent than organic mulches (Schonbeck and Evanylo 1998).

The benefit gained by using various mulch materials differs in different weather conditions. Radics and Bognar (2004) used eight types of mulches in a dry and a rainy year. In the dry year, tomato yield was equal best with paper, plastic or straw mulches, while in the rainy year, paper mulch gave the best result. Yield of green bean was not significantly different between mulch treatments in either year. Summer squash grew equally well on waxed, butcher, or polyethylene-coated kraft papers and black plastic mulch in one year, but in another year plastic mulch was significantly better than the other mulch material (Coolong 2010). Although mulch type significantly affected the total marketable yield of summer squash, there were several other environmental factors that contributed to the differences in yield.

In some cases, crop yields from paper mulch plots have equaled those obtained from polyethylene mulch plots (Harrington and Bedford 2004). Shogren and Hochmuth (2004) did not find differences in yields of watermelon (*Citrullus lanatus* Thunb.) when using kraft paper mulches treated with either soy oil or linseed (*Linum usitatissimum* L.) oil, or polyethylene mulches. Grassbaugh et al. (2004) did not find any significant differences in tomato yields between four different mulches, organic and inorganic, including shredded newspaper and black plastic. Similarly, Anderson et al. (1995) observed in Massachusets, USA that although the soil temperature beneath the brown paper mulch was lower, it gave similar tomato yields and earliness as black polyethylene mulch. When different paper mulch materials were compared Shogren and David (2006) found no significant differences in tomato and pepper yields between paper mulch systems (biodegradable brown kraft paper/cured vegetable oil and newspaper/straw). They showed that tomato and pepper production was equally good when using paper mulches treated with polymerized vegetable oil, newspaper/straw mulch, or manual weeding.

In some cases, yield under paper mulch was lower than under black plastic. In Zaragoza, Spain, tomato yields from plots covered with black plastic were highest, followed by paper, biodegradable plastic mulches and straw mulch (Anzalone et al. 2010). Hembry and Davies (1994) used paper, black plastic, and straw as mulch materials in production of savoy cabbage (*Brassica oleracea capitata* var. *sabauda* L.) in the UK. Although all mulches prevented weed growth very effectively, except straw that allowed some weeds to grow, they all reduced yield and mean head weight of the November harvest. By December, however, they all produced similarly to the manually weeded control plots.

Effects of paper mulch on yield also depend on the crop species (Table 4). When three paper mulches and black and white-on-black polyethylene mulches and bare soil were used for producing watermelon and pepper in northern Florida, the highest early and total watermelon yields were harvested from both plastic mulches, whereas the highest seasonal pepper yields were found with the three paper mulches and white-on-black polyethylene mulch (Hochmuth and Hochmuth 1994). The lowest yields were recorded from black plastic mulch and the no-mulch treatment. Peppers grown in northern Florida seemed to be better adapted to the use of paper mulches than watermelon. Miles et al. (2005) showed that different mulch products (Table 1) significantly affected broccoli and watermelon yields but not yields of lettuce and pepper in their field experiments in Washington, USA.

Table 4. Impact of paper mulch on yield as compared to bare ground

Crop	Paper quality	Effect on yield compared to bare soil	Location/country	Reference
bean, green bean	kraft paper, 70 g/m², recycled	positive	Budapest, Hungary	Radics and Bognar 2004
bean, soybean	shredded newspaper	posotive	Wooster, Ohio, USA	Munn 1992
cabbage	shredded paper glued between two brown paper	positive	Palmerston North, New Zealand	Harrington and Bedford 2004
calabrese	paper from recycle fibres	negative	Mepal, UK	Runham et al. 1998
corn, field corn	shredded newspaper	positive	Wooster, Ohio, USA	Munn 1992
corn, sweet corn	shredded newspaper	positive	Wooster, Ohio, USA	Munn 1992
cucumber, pickling cucumber	clupak paper	positive	Piikkiö, Finland	Pessala and Hårdh 1997
	clupak paper + clear PE film	positive/negative		
	clupak paper + black PE film	positive/negative		
	clupak paper, bituminized	positive		
	crepe kraft paper + black PE film	negative		
	crepe kraft paper + synthetic fibre	negative		
	MF-spinning paper	positive		
cucumber	newspaper sheets or shredded newspaper	NSD	Pennsylvania, USA	Sanchez et al. 2008
lettuce, head lettuce	kraft paper with several coatings	positive	Quebec, Canada	Brault et al. 2002a
lettuce	shredded paper glued between two brown paper	positive	Palmerston North, New Zealand	Harrington and Bedford 2004
lettuce	black paper mulch	NSD	Hohenheim, Germany	Matitschka 1996
lettuce	paper from recycle fibres	negative/positive	Mepal, UK	Runham et al. 1998
pepper	different qualities	positive	Florida, USA	Hochmuth and Hochmuth 1994

Table 4 continues

Crop	Paper quality	Effect on yield compared to bare soil	Location/country	Reference
pepper	brown kraft paper, oiled	NSD	Illinois, USA	Shogren and David 2006
potato	light grade durable paper	positive	New York, USA	Hardenburg 1932
pumpkin, summer squash	white butcher paper	positive	Kentucky, USA	Coolong 2010
	brown kraft paper	positive		
	brown waxed paper	positive		
	white kraft paper +PE film	positive		
rice	black paper with plastic film	positive	Suwon, Korea	Jeon et al. 2011
tomato	brown kraft paper	NSD	Zaragoza, Spain	Anzalone et al. 2010
tomato	shredded newspaper	positive	Ohio, USA	Grassbaugh et al. 2004
tomato	kraft paper	NSD	Leida, Catalonia, Spain	Martin-Closas et al. 2008
tomato	shredded or chopped newspaper	positive	West Virginia, USA	Monks et al. 1997
tomato	shredded newspaper	positive	Wooster, Ohio, USA	Munn 1992
tomato	kraft paper, 70 g m^{-2}, recycled	positive	Budapest, Hungary	Radics and Bognar 2004
tomato	brown kraft paper, oiled	NSD	Illinois, USA	Shogren and David 2006
watermelon	different qualities	positive	Florida, USA	Hochmuth and Hochmuth 1994

NSD - no significant differences

Environmental considerations

Use of plastics in agriculture and especially as mulches has already caused irreversible contamination of the soil in many parts of the world because only a fraction of the plastic is recycled. The plastics are not collected because of the high cost of labor to remove the films and also because of lack of economical disposal systems (Briassoulis 2006). Although all the starch-polymer blends used as biodegradable mulches might not be fully biodegradable (Zhang et al. 2008), they still represent an environmentally better alternative to plastics. Lately there has been growing interest in using paper mulches on account of their biodegradability and manufacture from renewable resources (Coolong 2010).

There has been concern about the safety of using newspapers as mulch, but 6 months after the application of a high rate of newspapers for mulching in Wisconsin, USA, no short-term impact was found on soil chemical properties such as organic matter or selected heavy metals (Munn 1992). When Runham et al. (1998) used paper mulch in the same location for three or four successive years, they did not find any deleterious effects to crops, and on average, paper mulches gave similar yields as plastic mulches.

The environmental benefits and the improvements of sustainability can justify the use of mulching with organic materials, particularly if the use of plastic mulches in agriculture is prohibited in the future (Anzalone et al. 2010), as is considered likely. New paper mulch products can in the near future compete well with plastics and biodegradable mulch films, particularly if environmental impacts are emphasized in agricultural production.

Economical considerations

In addition to the price of the mulch, the cost of mulching includes many other expenses also. The weight of the mulching material has big impact on transport costs. Ease of laying has a direct impact on labour expenses, and removal of mulch adds to labour costs. The disposal cost of nondegradable mulch, such as plastic, also has to be included.

Price of mulching materials

Black polyethylene is still the least expensive of the available mulch materials (Greer and Dole 2003), but because its extensive use causes significant and growing environmental problems, alternative and more environmentally friendly materials need to be found. Although biodegradable plastics (aliphatic polyesters) came onto the market as early as the 1980s, they have not become very widely used because they are rather expensive, and not all starch-polymer blends are fully biodegradable (Zhang et al. 2008). The price of biodegradable mulch film ranged between 0.23 € and 0.60 € m^{-2} depending on the size, quantity and quality of the material. The price of polyethylene mulch was much lower, 0.05 € to 0.08 € m^{-2}, depending on the material.

There are several kinds of paper mulches available for horticultural or agricultural use. Presently, the available paper mulches are particularly for small-scale use, because they are too expensive for any larger agricultural use. Retail prices of paper mulches (internet survey) ranged between 0.29 € and 1.06 € m^{-2} in 2011 depending on the size, quantity and quality of the material. In 2009, the producer price of common paper grades in Finland varied between 450 and 935 € per ton (Ylitalo 2010), so the large volume producer prices of papers having a basis weight 100 g m^{-2} is only 0.045−0.094 € m^{-2}. This suggests that paper mulches have the potential to become a much more cost-competitive option for farmers than they presently are. Furthermore, the disposal cost of plastic has to be taken into account, when economics of different materials are compared.

In 2004, the cost of oil-coated paper mulch, which is longer-lasting than paper alone, was about twice the price of polyethylene (610 $ oil coated paper cf. 250−370 $ polyethylene ha^{-1}) (Shogren and Hochmuth 2004). Earlier, Shogren (1999) calculated that the overall cost of using oil-coated paper as mulch was similar to that of polyethylene film when materials, transportation, removal and disposal of plastic at the end of the season were included. Miles et al. (2005) estimated that commercial Envirocare films (thermal/photo degradable plastic composed of polyethylene +TDPA) and 42-lb kraft paper were almost as expensive as plastic film, black plastic was slightly more expensive, and cornstarch-based Bio-Film about 3-4 times as expensive, and the cost of kraft paper varied greatly depending on the source. According to Anderson et al. (1995), commercial black mulch paper was considerably more expensive than black polyethylene film, but recycled kraft paper can be found in large rolls at a lower per-hectare price than polyethylene film.

Straw as mulching material was almost twice as expensive as shredded newspaper (~1.00 $ 60 ft^{2-1} row= ~5.6 m^2), and free sheets of newspaper were the cheapest alternative for mulching (Sanchez et al. 2008). Munn (1992) also showed that shredded newspaper from community recycling programs was an attractive alternative for agricultural production and soil management.

Other costs

Labor is expensive, especially in the developed countries, so the labor used in crop production is an important contributor to the price of the harvested marketable yield. Mulching is particularly interesting for farmers because it offers an opportunity to save labor and/or agricultural chemicals. For example, manual weeding used 16 times as much manual labor as paper mulching (Shogren and David 2006).

Paper mulch treated with polymerized vegetable oil could be economically suitable for higher value applications where biodegradable mulch is required (Shogren and David 2006). An obvious advantage of the use of paper mulches is that they can be left at the end of the season to degrade into the soil (Jenni et al. 2004), saving time and money with no detriment to yield in comparison with plastic mulch. Development of mulching and transplanting equipments together with the paper mulch materials is essential for large-scale production (Coolong 2010). Organic mulches can be a partial solution in many situations but they are more difficult to lay than plastic films, so their use become more costly (Greer and Dole 2003). Certain researchers believe that labor requirements can be significantly higher for applying plastic and paper mulches, and that they do not save as much time on weed controls as when using hay as mulch (Schonbeck and Evanylo 1998).

As a partial solution to the environmental problems caused by extensive use of plastics, paper mulch is nonetheless rather bulky and usually much heavier than any plastic, raising its relative cost of transport (Coolong 2010). From the economic point of view, paper mulches should be thinner but still durable enough to last the critical growth period of crops. As a good example, Shogren and David (2006) found no significant differences in field performance between two coated paper mulches, which made the thinner paper more economic choice.

New commercial paper mulch products tested by Harrington and Bedford (2004), or the use of vegetable oil to improve durability as introduced by Shogren and David (2006), are still quite new solutions. If these or similar products become more popular among farmers their widespread use could lower their price to an acceptable level, and in an optimal situation the wider marketing could further lower their price.

Conclusions

At present, plastic mulches are significantly more economical for mulching than the alternatives. However, when environmental considerations are taken into account, the situation might be different. There are already several paper mulch products on the market, but they are clearly too expensive for large-scale field production. The successful adoption of paper mulch by growers will depend on cost and availability (Jenni et al. 2004). More extensive use of paper mulches could bring the production price closer to plastics, but hardly to the level to compete with them if only the price of mulch is considered. Since paper mulch can be left in the soil after cultivation without any environmental concerns (Pessala and Hårdh 1977), its competitiveness with the widely used plastic mulches is increased, particularly in the presence of increased environmental awareness.

Although several studies have shown that some paper mulches can last a whole cropping season, there are also cases of damage from severe winds (Runham et al. 1998) that need to be considered when large areas of soil are covered. Hochmuth and Hochmuth (1994) also emphasized that for commercial adaptation, paper mulches still need improvements in application and planting equipment, as well as longer integrity of the buried paper tuck. Strengthening and further developing properties of papers for use in mulching is needed, because many paper products tested so far tend to degrade too fast, frequently before the end of the growing season (Schonbeck 1998, Anderson et al. 1995).

Numerous articles have been published about use of paper mulches. In spite of the interesting results they bring to light, it has been difficult to compare them in ways that explain the conflicting conclusions. Greer and Dole (2003) have also noticed the difficulty of comparing different published results of using different mulching materials. The studies tested only one hypothesis or very few, and not all of the essential factors that may contribute to higher yield, including number of insects, virus symptoms, seasonal rainfall, soil fertility, method of mulch application, were commonly reported. Furthermore, the studies were conducted in different climatic and geographical regions.

An advantage of paper mulches is that they do not create the disposal problem that plastic films always and partially degradable bio-films often cause. Paper mulches break down naturally after usage and incorporate into the soil. Laying paper mulches in large scale farming is a problem to be solved. The quality of the paper needs to be adapted or improved for mulching purposes, and its price needs to be more competitive with that of plastic mulches. Comparison of the current retail prices of paper mulches to the producer prices (Ylitalo 2010) shows that there is great potential to develop paper mulch products that are significantly more cost-competitive and a more suitable option for broader agricultural production. Because of the obvious environmental problem that the huge use of plastics in agriculture has created, it is not too difficult to foresee that there will soon be a great demand for better and cheaper paper mulches that are environmentally trouble-free.

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