REVIEW AND INTERPRETATION

Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches

S. S. Snapp,* S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, and K. O'Neil

ABSTRACT

The integration of cover crops into cropping systems brings costs and benefits, both internal and external to the farm. Benefits include promoting pest-suppression, soil and water quality, nutrient cycling efficiency, and cash crop productivity. Costs of adopting cover crops include increased direct costs, potentially reduced income if cover crops interfere with other attractive crops, slow soil warming, difficulties in predicting N mineralization, and production expenses. Cover crop benefits tend to be higher in irrigated systems. The literature is reviewed here along with Michigan farmer experience to evaluate promising cover crop species for four niches: Northern winter (USDA Hardiness Zones 5–6), Northern summer (Zones 5–6), Southern winter (Zones 7–8), and Southern summer (Zones 7–8). Warm season C_4 grasses are outstanding performers for summer niches (6–9 Mg ha^{-1}), and rye (*Secale cereale* L.) is the most promising for winter niches (0.8–6 Mg ha^{-1}) across all hardiness zones reviewed. Legume–cereal mixtures such as sudangrass (*Sorghum sudanese* L.)–cowpea (*Vigna unguiculata* L.) and wheat (*Triticum aestivum* L.)–red clover (*Trifolium pretense* L.) are the most effective means to produce substantial amounts (28 Mg ha^{-1}) of mixed quality residues. Legume covers are slow growers and expensive to establish. At the same time, legumes fix N, produce high quality but limited amounts (0.5–4 Mg ha^{-1}) of residues, and enhance beneficial insect habitat. Brassica species produce glucosinolate-containing residues (2–6 Mg ha^{-1}) and suppress plant-parasitic nematodes and soil-borne disease. Legume cover crops are the most reliable means to enhance cash crop yields compared with fallows or other cover crop species. However, farmer goals and circumstances must be considered. If soil pests are a major yield limiting factor in cash crop production, then use of brassica cover crops should be considered. Cereal cover crops produce the largest amount of biomass and should be considered when the goal is to rapidly build soil organic matter. Legume–cereal or brassica–cereal mixtures show promise over a wide range of niches.

COVER CROP choice depends largely on the objectives of a farmer, whether to prevent soil erosion, as a source of fertility, pest suppression, yield enhancement, or some other goal. In addition to defining objectives, a farmer needs to pay close attention to defining niches—spatial or temporal—where cover crops can be integrated into a farm. The research and farmer experience summarized in this paper are drawn primarily from the regions shown in Fig. 1. We contrast northern cropping systems, including USDA Hardiness Zones 5 and 6 of Northeastern and Upper Midwestern states, to southern cropping systems of USDA Hardiness Zones 7 and 8 from the U.S. Southeast and eastern California.

Overall, four niches for growing cover crops are considered: Northern winter cover crops (USDA Hardiness Zones 5–6), Northern summer cover crops (Zones 5–6), Southern winter cover crops (Zones 7–8), and Southern summer cover crops (Zones 7–8). The winter cover crop in the cooler zones complements a summer cash crop, while the summer cover crop in the warmer zones complements a winter or fall cash crop. Cover crops are thus inserted into niches that frequently remain fallow following conventional rotations (Creamer and Baldwin, 2000; Mutch and Snapp, 2003). Economic opportunity costs are much higher for the alternate niches, the Northern summer and Southern winter, because growing cover crops in these niches requires replacement of a cash crop with a cover crop.

Considerable research on cover crops has been conducted recently, indicating the need to review the literature and identify species that are consistent performers. Costs and benefits of cover crops are evaluated here in terms of both internal effects on individual farms, and external effects on society and the environment (Labarta et al., 2002). In contrast to the broad scope of environmental services from cover crops that may provide benefits to a broad cross-section of citizens, increased production costs are typically borne by individual farmers. This has policy implications, because beneficial economic "externalities" can justify government cost-sharing under federal programs like the Environmental Quality Incentives Program (Ogg, 1999).

There has been substantial research on winter annual cover crops (Kessavalou and Walters, 1999; Stivers-Young, 1998; Torbet et al., 1996; Wyland et al., 1998) and on summer cover crops for the Southeast and southern U.S. desert regions (Creamer et al., 1997; Creamer and Baldwin, 2000; Ngouajio et al., 2003). The other two niches considered here, Northern summer and Southern winter, have received less study. Despite the economic impact of foregoing a cash crop, some farmers express interest in planting cover crops in these niches, particularly for fields that require rehabilitation. For example, Michigan and New York producers are experimenting with summer cover crops to ameliorate degraded soils and persistent pest problems (Snapp and Mutch, 2003; Stivers-Young and Tucker, 1999).

The objectives of this paper are to (i) review the literature on the costs and benefits associated with cover

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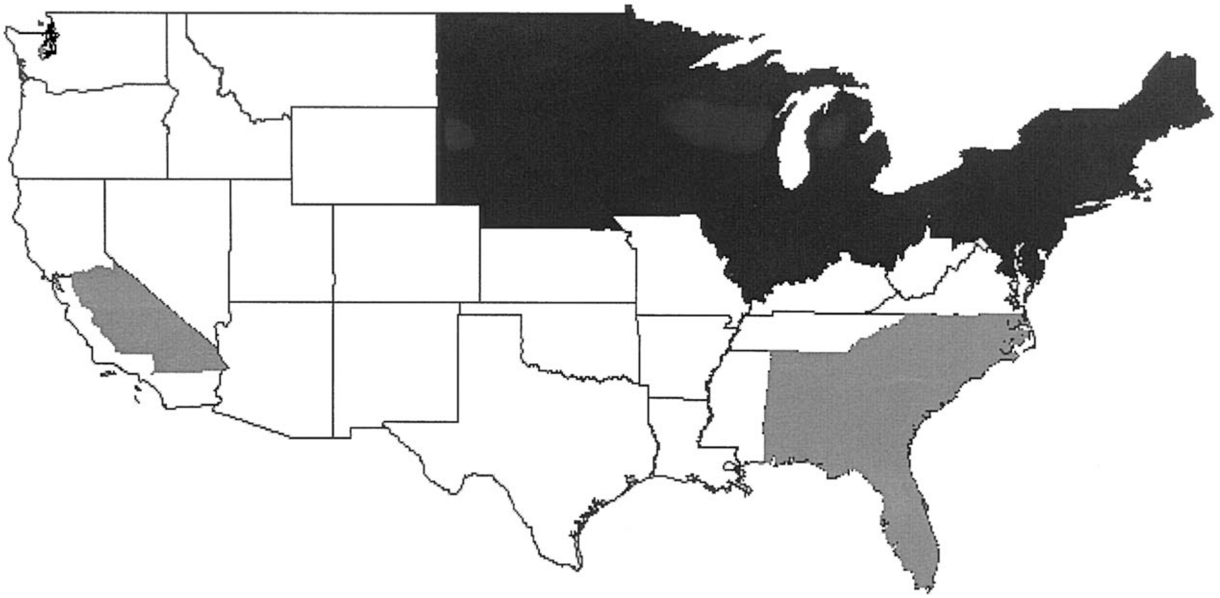

Fig. 1. The literature reviewed in this paper is categorized as being conducted either within a northern region (USDA Hardiness Zone 5–6) or a southern region (USDA Hardiness Zone 7–8). A winter and a summer cover crop seasonal niche is considered for each of these regions. The northern region is shown in black on the map and includes the Northeast and Upper Midwest. The southern region is shown in gray on the map and includes the Southeast and Zone 7–8 in California.

crops; (ii) report findings from Michigan farmer assessment of cover crops, and (iii) identify promising species options for four cover crop niches (USDA Hardiness Zones 5–6 winter, Zones 5–6 summer, Zones 7–8 winter, and Zones 7–8 summer).

ECONOMIC REVIEW

Adoption of cover crops has been limited (Mallory et al., 1998) despite the evident environmental services provided and the range of benefits documented in the following literature review. Nowak (1992) contends that farmers fail to adopt new technologies either because they are unwilling or unable. Unwillingness frequently arises from unattractive incentives, such as low profitability. Inability arises either from ignorance or some other barrier. While information gaps abound regarding the performance of cover crops, most other barriers to adoption in the USA are likely to be surmountable. More important are apparent disincentives to adoption of cover crops. If cover crops offer net benefits that extend beyond the farm gate, there may be a rationale for public subsidies to support continued provision of socially beneficial externalities. To provide a balanced overview, we review the literature on both internal and external effects of cover crops, reporting also on qualitative assessments from Michigan farmer focus groups.

Benefits External to the Farm

Socially desirable benefits of wide-spread adoption of cover crops derive from soil conservation properties. A number of studies have found that duration of crop cover is a primary determinant of reduced soil erosion and nitrate leaching. Creamer et al. (1997) found that 13 cover crops and mixtures (mainly legumes) achieved 30% ground cover 1 mo after planting in North Carolina, and generally 100% cover within 3 mo. Field pea (*Pisum sativum*) provided adequate surface cover to control soil erosion effectively in a 4-yr rotation of wheat–fallow (Tanaka et al., 1997). In Norwegian cropping systems, 100% ground cover was rapidly achieved by subterranean clover (*Trifolium subterraneum* L.), although hardiness of this species was marginal and more long-lasting ground cover was achieved using hairy vetch (*Vicia villosa* Roth.) (Brandsaeter et al., 2000). Hairy vetch is also an effective means to provide soil coverage and build soil organic matter in the Southern USA, as shown in a Georgia field study (Sainju et al., 2002).

Winter cover crops are of particular benefit on irrigated, sandy soils where bare soil is readily erodible if left unprotected during the colder months (Table 1). Winter cereals grown as cover crops, such as rye and wheat, can be highly effective at reducing wind and water erosion (Kessavalou and Walters, 1999; Kinyangi et al., 2001), and the combination of covers plus reduced tillage is a rapid means of building soil organic matter (Sainju et al., 2002). Surveys indicate that 25% of Western New York vegetable growers and 43% of Michigan potato (*Solanum tuberosum* L.) producers use winter cereals as cover crops to reduce erosion (Snapp et al., 2001; Stivers-Young and Tucker, 1999).

Nitrate leaching and agro-chemical surface runoffs are two important environmental effects that reach beyond farm boundaries. Wyland and colleagues (1998) found that cover crops rye and phacelia (*Phacelia tanacetifolia* L.) were effective at taking up N and water, reducing nitrate leaching by >70% in irrigated broccoli (*Brassica oleracea* var. *italica*). Similarly, winter cover crops enhanced recycling of inorganic N by >50%, and markedly reduced nitrate leaching in irrigated potato systems of the Pacific Northwest (Weinert et al., 2002).

Table 1. Benefits associated with cover crop systems used in the Midwest and Northeast regions, Hardiness Zones 5 and 6. Summarized from literature review and grower comments from two focus groups with 11 Michigan potato industry representatives.

Cover crop system	Literature review–system benefits	Citation	Grower comments–benefits
Conventional winter rye cover crop after potato	• Protects soil from erosion: rye achieved 30% or higher soil cover after 1 mo, compared with a bare fallow • Nitrate-N leaching reduced by 22–56 kg N/ha in sweet corn and broccoli (compared with bare) • Rye cover improves soil structure and water holding capacity by increasing stability of soil aggregates compared with bare fallow	Burket et al., 1997 Creamer et al., 1997 Kinyangi et al., 2001 Stivers-Young, 1998	• This practice used widely, as it minimizes opportunity costs: no cash cropping opportunity is limited • Rye is the most reliable cover crop for establishment in late fall after vegetable or potato harvest, and has excellent winter survival • Rye consistently provides good protection against wind
Red clover, overseeded as a relay crop in wheat or corn rotated with a vegetable	• Protects soil from erosion • Reduces number of tillage operations, preventing soil compaction • Builds soil organic matter • Corn yields after wheat/clover about 15% higher than with no cover • Broccoli yields 0–45% higher after a relay red clover cover crop compared with winter fallow or rye cover crop	Burket et al., 1997 Jones et al., 1998 Mutch and Martin, 1998	• Growers use this practice now, occasionally • Ease of adoption: minimal change in current rotation sequences required, plant clover into cereal crop in rotation • Interested to see if increases potato yield 5600 kg/ha and increases soil water holding capacity
Legume or brassica mixed winter cover with rye	• Protects soil from erosion, reduces N loss • Biological N fixation from legumes provide a slow release N source to support crop growth • Break pest cycles and reduce parasitic nematodes • Diversifying species may enhance soil microorganism activity, build soil N supply capacity and improve nutrient efficiency	Gallandt et al., 1998 Nyiraneza, 2003 Sanchez et al., 2001	• Ease of adoption: minimal change in current rotation sequences required, plant mustard and/or legume mixed with a cereal rye cover crop • Interested to see if increases potato yield 5600 kg/ha and increases soil water holding capacity
Alfalfa or other forage rotation	• Potato tuber yield increases after 2 yr alfalfa or vetch rotation • Associated with 50% reduction in *Rhizoctonia solani* infection and can provide 45–67 kg/ha fertilizer equivalent • Plow down N of 118–269 kg/ha after 1 yr alfalfa or vetch grown as a green manure • Can break some pest cycles and reduce disease susceptibility (or increase it)	Honeycutt et al., 1996 Griffin and Hesterman, 1991 Stivers-Young and Tucker, 1999 Creamer et al., 1996	• Alfalfa sometimes used as a summer cover crop by potato and vegetable growers • Alfalfa rotations sometimes reduce fumigation requirements

Foltz et al. (1993) used the CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) model to simulate chemical runoff in corn (*Zea mays* L.)–soybean rotations, finding that replacing soybean with alfalfa (*Medicago sativa* L.) was associated with reduced runoff of metolachlor and bentazon. In a field study, Vyn et al. (1999) found that annual ryegrass could substantially reduce nitrate leaching risk in corn systems. Reduction in nitrate leaching losses is also possible through planting a winter rye cover, as observed for Michigan field crop systems (Kinyangi et al., 2001). However farmer adoption of winter rye will only reduce N leaching if extra N fertilizer is not applied when planting the cover crop (Snapp et al., 2001).

Costs External to the Farm

Integrated cropping systems bring costs as well as benefits to the farm and the environment (Table 2). Research on environmental effects has identified potentially negative consequences, particularly if cover crops are mismanaged. The presence of a vigorous cash crop or alternate cover crop is important to establish as a N-sink after a cover or forage is incorporated. Unless N is assimilated, there is considerable potential for N losses through leaching or volatilization from N-rich residues (Rosecrance et al., 2000). This is shown by soil nitrate monitoring after alfalfa incorporation, where high nitrate leaching rates were measured if establishment problems were encountered and the subsequent corn crop did not achieve an adequate plant population density (Rasse et al., 1999). Alfalfa and other deep-rooted cover crops may also enhance the formation of macropores in soil, which could increase water percolation and thus nitrate leaching under some circumstances (Foltz et al., 1993).

Benefits Internal to the Farm

Benefits internal to the farm are diverse (Table 1). Some environmental benefits relate to both the farm and the landscape; however, if the primary effects go to the farm, we consider these benefits as internal. Increased yield of a marketable crop is the most direct

Table 2. Costs and problems associated with cover crop systems used in the Midwest and Northeast regions, Hardiness Zones 5 and 6. Summarized from literature review and grower comments from two focus groups with 11 Michigan potato industry representatives.

Cover crop system	Literature review–system problems	Citation	Grower comments–problems
Conventional winter rye cover crop after potato or other cash crops	• Initial N immobilization on incorporation of rye residues • Delayed planting of cash crop	Burket et al., 1997 Stivers-Young and Tucker, 1999	• Can become too vigorous in the spring, challenging to incorporate residues • Lack of appropriate equipment for residue incorporation
Red clover, over-seeded as a relay crop in wheat or corn	• Germination and establishment problems • High cost of establishment • N credit difficult to calculate for subsequent crops • Fertility management can be challenging with a wide range of residue quality	Mutch and Martin, 1998 Vyn et al., 1999	• Red clover may be associated with scab, a major disease problem in potato • Need a wider range of legume species that are shade and cold tolerant and can be overseeded into cash crops • Concern about estimating N availability to subsequent crops after red clover and wheat stubble incorporated
Legume or brassica mixed winter cover with rye	• Expense of mustard and legume cover crop seed • Delayed planting	DeGregorio, 1995 Labarta et al., 2002	• Potential weed problems from escaped progeny of mustard and hairy vetch
Alfalfa or other forage rotation	• Limited profitability • Opportunity costs • High cost of establishment • Can increase risk of some diseases	Abawi and Widmer, 2000 Labarta et al., 2002 Posner et al., 1995 Stivers-Young and Tucker, 1999	• Forage market very limited • Costs can be high and limited returns • Residues can be difficult to incorporate • N credit difficult to estimate • Forage harvest management requirements high, so interest is in alfalfa as a cover crop not a hay crop • Soil acidity (used to control potato scab) tends to reduce establishment of alfalfa

benefit that can be derived from growing cover crops. In a rotation trial where yields were not consistently increased, and establishment costs were significant, the profitability of red clover interseeded with corn was highly variable (Jones et al., 1998). Soil organic C and soil N mineralization potential increased over time with the integration of legumes in the Pennsylvania experiment (Drinkwater et al., 1998). Similar trends were observed in a hairy vetch tomato (*Lycopersicon esculentum* Mill.) system (Sainju et al., 2002). The trend is for consistent use of cover crops to build soil organic matter, which enhances yield potential through increasing soil water holding capacity, aeration, and nutrient supply capacity.

Greater yield stability is an important secondary benefit of cover crops. A long-term field study in Pennsylvania found, in drought years, that yield of organic corn and soybean–cover crop systems was higher than conventionally produced field crop systems grown without cover crops (Lotter et al., 2003).

Soils with a higher nutrient supply capacity require reduced fertilizer inputs. If fertilizer costs are reduced while yield is maintained, profitability over the long-term may more than compensate the immediate costs of cover crop establishment. Examples include the contribution of red clover and crimson clover (*Trifolium incarnatum* L.) to corn and barley (*Hordeum vulgare* L.) yields (Drinkwater et al., 1995; Sweeney and Moyer, 1994; Torbet et al., 1996; Vyn et al., 1999) and the positive effect of berseem clover (*Trifolium alexandrinum* L.) in a corn–soybean–oat (*Avena sativa* L.) rotation (Ghaffarzadeh, 1997). In potato-based rotations, legume cover crop residues supplied 25 to 260 kg ha^{-1} N to a subsequent crop (Griffin and Hesterman, 1991; Honeycutt et al., 1996). More recently, potato yields were enhanced by 16% and N fertilizer use reduced by 10% after a mixed cover crop of rye–hairy vetch compared with a bare winter fallow (Nyiraneza, 2003; Snapp et al., 2003). Hairy vetch grown as a winter cover crop supplies from 50 to 120 kg N ha^{-1} to subsequent tomato crops (Sainju et al., 2002; Teasdale and Abdul-Baki, 1998; Yaffa et al., 2000).

Cover crops also control weeds through competition, allelopathy, soil environmental changes, physical effects, enhancement of weed seed decay, and maintaining surface residues (Conklin et al., 2002; Creamer et al., 1996). Weed suppression can reduce herbicide use resulting in lower production costs. Stivers-Young (1998) found that oilseed radish (*Brassica napus* L.) and mustards [*Brassica juncea* (L.) Czern.] suppress the majority of weeds compared with a bare fallow, primarily through competition in the fall and light interception by the residue in spring. Cover-crop mediated suppression was found in tomato (Creamer et al., 1996), peppers (*Capsicum annuum* L.) (Hutchinson and McGriffen, 2000), and in potato (Gallandt et al., 1998). Weed reduction was reported as a benefit by 15% of vegetable growers surveyed in New York (Stivers-Young and Tucker, 1999), and <5% of potato growers surveyed in Michigan (Snapp et al., 2001).

Cover crops have been shown to break disease and pest cycles, reducing the need for fumigation and pesticides. Reduced pesticide use lowers production costs and may offer environmental benefits both internal and external to the farm. Incorporation of a short alfalfa rotation reduced *Rhizoctonia solani* infection in potato by 50% (Honeycutt et al., 1996). Lazarus and White (1984) described chemical-use reduction through the integration of a rye cover crop into a range of cropping systems including potato, cauliflower (*Brassica oleracea* L.), beet (*Beta vulgaris* L.), and bean (*Phaseolus vulgaris* L.). Gebremedhin et al. (1998) found that alfalfa provided important disease and pest-suppressing benefits in irrigated sugarbeet (*Beta vulgaris* L.) and bean systems. Nematode control, and the potential to reduce fumigation frequency, is promoted by some brassica species (McGuire, 2002; Porter et al., 1998). Suppression of *Pythium* spp. has been observed subsequent to incorporating glucosinolate-containing brassica cover crops, although this response is not always consistent (Abawi and Widmer, 2000; Lazzeri and Manici, 2001).

Longer-term studies than many of those conducted to date may be required to document the pest and nutrient cycling consequences of adopting cover crop (Drinkwater, 2002). This point is supported by a comprehensive on-farm study of 100 commercial potato fields, which found that soil organic matter was inversely related to *Verticillium wilt* (Davis et al., 2001).

Costs Internal to the Farm

Internal costs of cover crops take three forms: direct, indirect, and opportunity costs. The direct costs of cover crops are led by the costs of cover crop establishment, which are particularly high for legumes. Establishment costs can be 10 times higher for leguminous cover crops than for grasses (Labarta et al., 2002; Roberts and Swinton, 1996). This is due to legume biological traits that drive up seed costs and the amount of seed required for establishment, including a large seed size (this necessitates substantial seed weight be used at planting), seed dispersal mechanisms (this increases harvesting expense and thus the cost of legume cover crop seed), and generally weak emergence (requiring investment in practices such as tillage, irrigation, and fertilizer, as well as high seeding rates).

The indirect on-farm costs of cover crops fall into two categories: (i) hindering establishment of the succeeding cash crop (due to slow soil warming or delayed organic N release) and (ii) cover crop management problems that impede realization of the expected benefits (e.g., due to over-vigorous cover crops that are hard to kill or incorporate, or virulent cover crops that become weeds).

The leading cause of impeded cash crop establishment is slow soil warming. Stivers-Young and Tucker (1999) found that cover crops of clover, wheat, and rye shaded the soil, slowing the spring rise in soil temperatures on potato and vegetable farms in New York. This is not universally a negative aspect of cover crops, as soil cooling effects of cowpea residues were beneficial for desert vegetable production (Hutchinson and McGiffen, 2000).

An indirect cost of using cover crops as a nutrient source is the slow rate of N release from nonlegume cover crop residues, and the difficulty of accurately estimating residue mineralization, which can reduce synchrony of nutrient release with crop demand (Snapp and Fortuna, 2003). Initial N immobilization generally occurs for the first 2 mo after winter cereal cover crops are incorporated, although residue management can markedly alter the timing of N release (Snapp and Borden, 2004; Vyn et al., 1999). In addition to slow release of nutrients, mineralization of excess or unexpectedly high levels of N late in the growing season can occur after higher quality residues from legumes are incorporated (Griffin and Hesterman, 1991).

Overly vigorous cover crops can exact unexpected costs to kill the cover crop or to incorporate its residues into the soil. Cover crop biomass produced can be substantial, which leads to mechanical difficulties in incorporating residues if cover growth is allowed beyond about 30 cm in height.

Successful cover crops can become difficult to control. It is important to prevent cover crops from producing seed and establishing in areas where they will act as weeds (Mutch and Snapp, 2003). There are a number of covers that produce seeds with hard coats or other adaptations that can become part of the weed seed bank and germinate over many years (Benech-Arnold et al., 2000).

The opportunity cost of income foregone from cash crops may be the biggest cost of cover crops and the chief reason that they are rarely grown during periods when cash crop alternatives are feasible. Most evidence comes from whole-farm linear programming models that can estimate the opportunity cost in foregone earnings from forcing an enterprise into solution that was not optimal. While we are aware of no such studies that explicitly examine cover crops, a number of studies have explored the opportunity costs associated with crop rotations that include less remunderatives crops whose primary benefits come from reduced soil erosion or enhance N fixation.

Inclusion of soil-building rotation crops with potato in Long Island (Lazarus and White, 1984) and with corn and soybean in Michigan (Roberts and Swinton, 1995) both led to reduced net returns. Likewise, crop rotations based on corn–soybean or sugarbeet–dry bean that added small grains and/or alfalfa for reduced erosion and enhance fertility achieved the latter objectives but failed to deliver comparable net returns (Baffoe et al., 1987; Foltz et al., 1993). Enterprise budget analyses that do not explore the opportunity cost of farm resources shared across crop enterprises have had mixed results, with some showing cropping diversity to be profitable (e.g., Helmers et al., 1986) and others not so (e.g., Christenson et al., 1995). Although direct study of cover crop effects remains a research need, the evidence from prior whole-farm studies of crop rotations suggests that opportunity costs due to foregone income from cash crops can be an important disincentive to crop rotation and, by extension, to the adoption of cover crops that compete in time or space with cash crops.

FARMER ASSESSMENT

Producers provide valuable insight into practical management issues that act as barriers to adoption of cover crops, as well as unexpected benefits that might increase adoption (Posner et al., 1995). In the winter of 2002, two focus group discussions were held with eight Michigan potato farmers and three crop consultants who altogether farm about 11 000 ha, 60% of the potato area in Michigan (Tables 1 and 2). Participants were asked open-ended questions to elicit perceived problems and benefits associated with different cover crop species, establishment strategies, niches for integration into cropping systems, and residue management practices. A primary concern of focus group members was the opportunity cost associated with cover crops that replace cash crops, and the cover crop systems seen as adoptable did not limit cash cropping opportunities (Table 1). Farmers also voiced concerns about accurately predicting N supply and the potential for disease-enhancement associated with legumes (Table 2). More attention to evaluating opportunity costs in farm budget decision tools could provide valued information. Although considerable research has been done on legume cover crop residues as N sources (Griffin and Hesterman, 1991; Sainju et al., 2002), farmers generally use cereal cover crops, and there may need to be more research that addresses predicting N mineralization from these residues (Snapp and Fortuna, 2003).

Interseeding a cover crop into a cereal crop was discussed by growers, including frost-seeding a red clover into wheat (broadcasting red clover seed in early spring on a wheat crop) and aerial-seeding rye into corn, just before harvest. This approach minimizes opportunity costs, and was seen by most growers as about the only practical and economical means to produce a winter cover crop with large quantities of biomass (Table 1). A winter wheat crop interseeded with red clover allows the soil to remain undisturbed for 17 mo, combining cover crop inputs with reduced tillage to build soil organic matter (Snapp et al., 2003). Red clover and cereal rye were suggested as the best cover crops options to establish and survive a low light and competitive environment under a canopy. However, some farmers associated red clover with common scab (*Streptomyces scabies)* incidence in potato (Table 2). Alternative cover crops adapted to interseeding into grain crops were requested by growers. Promising research along this line includes efforts to find minimally competitive understory crops to sow in soybean–corn rotation sequences (DeHaan et al., 1997; Hively and Cox, 2001; Smeltekop et al., 2002).

Farmers that grew shorter-season crops such as snap bean or corn silage were experimenting with a wide range of winter cover crops, including buckwheat (*Fagopyrm esculentum* Moench), sweetclover (*Melilotus officinalis* L.), and oilseed radish. After long-season crops that are harvested late in the fall such as potato there are limited options for winter cover crops. Only wheat or rye, and in some cases rye mixtures with hairy vetch, were seen as sufficiently cold-hardy to survive planting late in the fall (Table 1).

Growers were also interested in using cover crops to ameliorate a poor site. This requires a willingness to substitute a cover crop for a cash crop in the summer niche to grow large amounts of biomass, for example sorghum–sudangrass [*Sorgum bicolor* (L.) Moench × *S. sudanesnse* L.]. Michigan growers reiterated that it is critical to manage for higher quality residues by limiting stem growth (Table 1). Other growers surveyed were more impressed by alfalfa managed as a cover crop, citing the "biological plow" effects of alfalfa's deep tap root and the N-enriched residues. A New York survey of vegetable growers supported these observations, as sorghum–sudangrass and alfalfa were the most common summer cover crops grown (Stivers-Young and Tucker, 1999).

On the whole, the literature and farmer observations coincide and indicate that substantial benefits can accrue from incorporating cover crops, ranging from environmental enhancement to cropping system health (Table 1). Farmers emphasized as well the risks associated with cover crop adoption, such as inadequate equipment or time to incorporate residues and less predictable N release compared with reliance solely on inorganic fertilizers (Table 2). This suggests that improved knowledge concerning management practices, residue quality, and N release could promote adoption of cover crops (Snapp and Borden, 2004). To assist growers and extension crop advisors interested in experimenting with cover crops, we offer information on species performance and "best bet" cover crop options for different niches in the next section.

PROMISING COVER CROP OPTIONS

Trends in performance are reviewed here for cover crop families, to identify promising species for four cropping system niches: Northern winter cover crops (USDA Hardiness Zones 5–6), Northern summer cover crops (Zones 5–6), Southern winter cover crops (Zones 7–8), and Southern summer cover crops (Zones 7–8A).

In general, cover crops appear to perform better in irrigated systems where competition for water and nutrients is reduced, thereby enhancing potential returns to cover crop investments. This observation is supported by the substantial number of farmers with irrigation that have adopted cover crops in Northern states (Snapp et al., 2001; Stivers-Young and Tucker, 1999). In systems without irrigation, nitrate leaching is more limited and moisture competition between cover crop and cash crop must be considered. An Ohio study found that field pea–rye mixture produced >4 Mg ha^{-1} biomass and enhanced productivity of a subsequent tomato crop, but only when moisture was adequate (Akemo et al., 2000). Surprisingly, annual medic grown as an intercrop in corn competed for N, but did not induce water stress, possibly due to enhanced water infiltration compared with conventionally grown corn with bare rows (Smeltekop et al., 2002). The impact of cover crops on water relations over time can be complex, as shown for cropping systems of the Northern great plains: yields of flax (*Linum usitatissimum* L.) and mustard were substantially reduced by intercropped sweetclover in dry years, whereas yield of the rotational wheat crop was enhanced by 47 to 75%

when sweetclover replaced a tilled fallow (Blackshaw et al., 2001).

Northern Summer Cover Crops

The summer niche in Northern climates requires substitution of a cash crop with a cover crop, but it is used by farmers to rehabilitate poor-performing fields. A C_4 grass such as sorghum sudangrass [*Sorghum bicolor* (L.) Moench] is best able to use resources in a warm, high light environment and produce tremendous amounts of biomass, often more than 8 Mg ha^{-1} (Fig. 2). The quality of this biomass is very low (N content <1%), but it contributes substantially to soil C. Farmers surveyed in Michigan and New York plant sorghum sudangrass more frequently than any other summer cover crop (Snapp et al., 2001; Stivers-Young and Tucker, 1999). Management and timing of this cover is critical to facilitate residue decomposition and to reduce allelopathy and problems with stand establishment in subsequent crops (Ngouajio et al., 2003; Weston et al., 1989). The earlier cited farm surveys indicate that alfalfa, managed as a cover crop, is the primary alternative to C_4 grasses. Growers cite the high quality of the residues (Table 1) as an inducement despite the relatively moderate quantity of biomass produced (Fig. 2). Alfalfa is, however, an expensive crop to establish and there can be problems with managing the high-N residues (Rasse et al., 1999).

Research has documented the ability of mixed grass–legume cover crop systems to consistently produce large amounts of diverse residues (Fig. 2). Residue mixtures of high and low quality appear to be particularly effective at enhancing soil quality by building active organic matter pools (FrancoVizicano, 1997; Puget and Drinkwater, 2001; Sanchez et al., 2001). Root system characteristics tend to be complementary between grasses and legumes, where superficial fine roots of grasses ameliorate shallow compaction and tap-rooted legumes reduce deep compaction. Mixed cover crops are frequently able to establish and thrive despite degraded soils or uncertain weather (Mutch and Snapp, 2003). Mixtures also have relatively low establishment costs. Consistent performers that produce ~4 to 7 Mg ha^{-1} of biomass are sweetclover–oat (1:2 or 1:5 ratio of sweetclover to oat plants) and cowpea–sorghum sudangrass (Fig. 2; Schmidt et al., 2001).

Northern Winter Cover Crops

Winter cover crops can be grown in this niche without sacrificing a cash crop, although establishment can be a challenge. The common planting window used is in the fall, after harvest of a cash crop. For short-season cash crops such as snap bean (*Phaseolus vulgaris* L.) or corn silage there are a wide range of cover crop species that can be established in this August to September time-frame (Stivers-Young, 1998). However, for crops harvested in the late fall only the most winter-hardy cover crop species can survive, such as hairy vetch and rye (Snapp et al., 2003). Overseeding a cover crop into a small grain crop or into corn is the other primary means of establishing a winter cover.

Winter cereals such as rye and wheat have extensive root systems and provide persistent soil cover; thus, they are effective at scavenging inorganic N and preventing soil erosion (Burket et al., 1997; Kessavalou and Walters, 1999). Rye produces between 0.8 and 2.9 Mg ha^{-1} biomass when fall-sown in Michigan (Fig. 2). Similar biomass production levels have been observed in surrounding states (Fig. 2; see Akemo et al., 2000; Vyn et

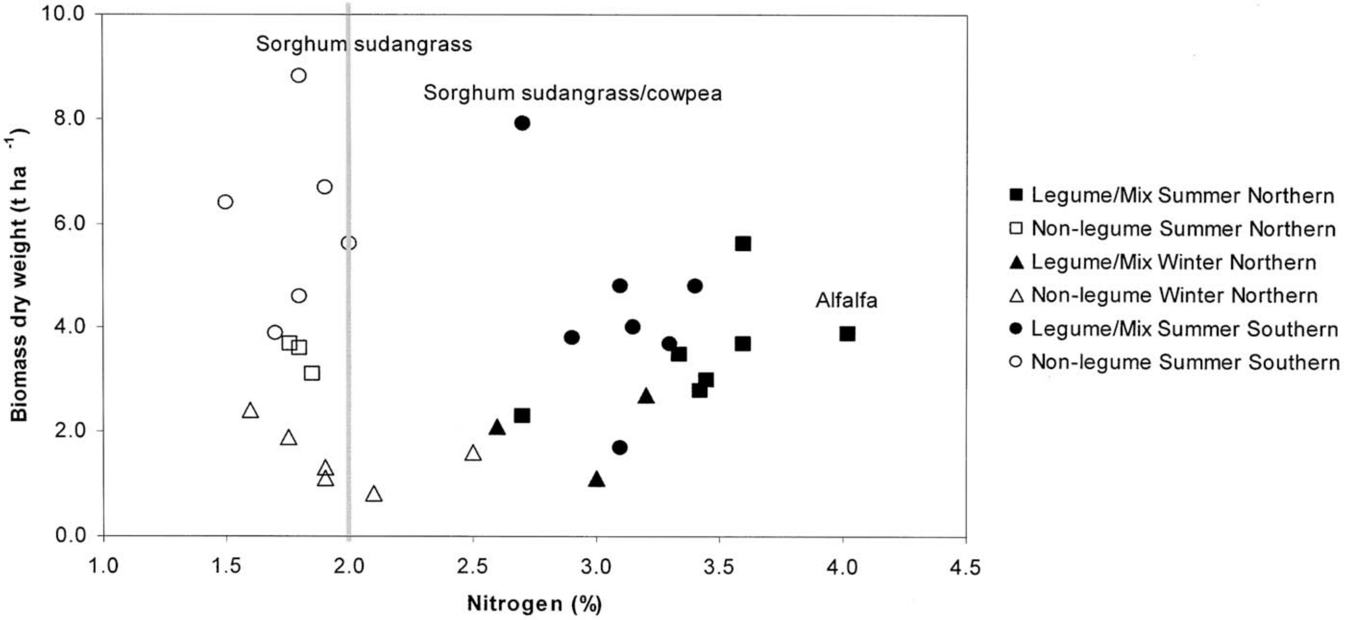

Fig. 2. Shoot biomass produced (*y* axis) is presented vs. N concentration of biomass (*x* axis) for cover crops grown during the summer in the north, during the summer in the south, and during the winter in the north. The cover crops were categorized as either a nonlegume or a legume/mix (sole legume or a mixture with legume). The C/N ratio of 23 (equivalent to a tissue N concentration of 2%) bisects the figure and residues on the right side are expected to mineralize N. Data is from Creamer and Baldwin, 2000; Justes et al., 1999; Mutch et al., 2001; Schmidt et al., 2001; and Snapp et al., 2003.

al., 1999). The rapid growth of rye in the spring may require management practices such as herbicide application or mowing to facilitate residue incorporation and enhance N mineralization (Snapp and Borden, 2004). Brassicas also show potential as rapid N accumulators that can reduce nitrate leaching potential by >50% in Northern climates (Justes et al., 1999).

As described for the summer niche, a mixture of grasses and legumes can be used for winter cover. Erect cereal and viney legume growth habits can be highly complementary. They frequently produce larger amounts of biomass when they are planted together than when they are planted as sole crops (DeGregorio, 1995; Ranells and Wagger, 1997; Rosecrance et al., 2000). The mixed residues produced provide a diversity of substrate that supports soil microbial activity (Ovreas and Torsvik, 1998; Sanchez et al., 2001). Hairy vetch is the most versatile of winter-hardy legumes, it is well adapted to mixtures with rye and produces biomass that is consistently >2 Mg ha^{-1} with a C/N ratio below 22. This was observed in southern Michigan with hairy vetch and rye planted as late as October (Snapp et al., 2003). A red clover–cereal biculture is an outstanding candidate, as red clover has the ideotype of an ideal intercrop: establishing as an interseeded cover in corn or wheat, tolerant of low light, and consistently producing about 3.0 Mg ha^{-1} of high quality residues (Fig. 2). Red clover appears to be highly compatible with wheat, but not as an intercrop with soybean in New York (Hively and Cox, 2001). The legume mixtures in the Northern niche shown in Fig. 2 are red clover and hairy vetch cereal mixtures. None produced >3 Mg ha^{-1} (Fig. 2), but red clover intercropped with wheat has been shown to substantially enhance soil C and N mineralization potential in three Michigan trials (Mutch and Martin, 1998; Sanchez et al., 2001; Snapp et al., 2003) and in Ontario sites (Vyn et al., 1999).

If pest control is a major concern, then other species than legumes or grasses should be considered. Disease suppression has been observed with integration of alfalfa (Gebremedhin et al., 1998; Honeycutt et al., 1996), but the most effective cover crops for suppression of plant parasitic nematodes (Porter et al., 1998) or soilborne diseases appear to be glucosinolate-containing brassica (Lazzeri and Manici, 2001). Winter survival in Zones 5–6 is uncertain and the biomass accumulated by oilseed radish and oriental mustard is highly variable, but 4 Mg ha^{-1} has been observed under Michigan conditions (Mutch et al., 2001). Fall-planted oriental mustard is being rapidly adopted in irrigated systems of the Pacific northwest to suppress soil-borne disease and nematodes (McGuire, 2002). More than 10 000 ha of mustard are being grown as a managed cover crop, where irrigation and N fertilizer are applied to optimize the biomass produced. This indicates the potential for rapid adoption of cover crops that are effective at reducing a major input cost (e.g., fumigation) and that have immediate productivity or crop health benefits.

Southern Summer Cover Crops

Summer establishment of cover crops in warmer zones requires heat-tolerant species that grow rapidly. Not surprisingly, the warm-season grass sorghum–sudangrass was the outstanding biomass producer in a range of species evaluated by Creamer et al. (1997). Cowpea was less productive (4 Mg ha^{-1}) in that study but has been shown in other summer cover systems to produce 6 to 8 Mg ha^{-1} (Hutchinson and McGriffen, 2000). Cowpea is as effective as sorghum–sudangrass in suppressing weeds in irrigated systems, while being consistently associated with yield enhancement in subsequent crops (Ngouajio et al., 2003). The same study documented crop suppression subsequent to sorghum–sudangrass incorporation, indicating the need for caution and knowledge concerning cover crop management.

Pest suppression properties are frequently associated with tropical legumes, which provides a wide range of options for Zone 7–8. Tropical legumes such as pigeonpea [*Cajanus cajan* (L.) Huth], showy crotalaria (*Crotalaria spectabilis* Roth), hairy indigo (*Indigofera hirsuta* L.), joint-vetch (*Aeschynomene america* L.), and velvet bean [*Mucuna deeringiana* (Bort) Merr.] consistently reduced plant parasitic nematodes and increased yields in subsequent irrigated snap bean production in Florida (Reddy et al., 1986). Sunn hemp (*Crotalaria juncea* L.) has also shown promise as a pest suppressing, alternative summer cover crop (Mansoer et al., 1997). In general, viney or indeterminate growth habit and long-duration growth (8–18 mo) habit legumes such as pigeon pea and Mucuna [*Mucuna pruriens* (L.) DC var. utiliz] appear to be the most effective cover crops at increasing N availability to the cash crop (Snapp and Silim, 2002).

Southern Winter Cover Crops

From the limited research conducted on this niche, it appears that the grass and legume species that perform well in winter Zone 5–6 are generally adapted to Zone 7–8 (Shennan, 1992). Jackson et al. (1993) demonstrated that substantial cover crop biomass could be produced by winter-grown rye and legumes in California. Soil nitrate leaching was reduced by >50 kg ha^{-1} N through integration of these winter cover crops in irrigated vegetables. Similarly, winter cover crops rye and phacelia were effective at recycling N in irrigated lettuce (*Lactuca sativa* L.) (Wyland et al., 1998). Efficient suppression of weed growth as well as N-recycling occurred with the use of a winter cover cereal rye and rye–bellbean (*Vicia faba* L.) mixture in a coastal cabbage (*Brassica oleracea* L.) rotation, although bellbean alone was not effective at weed suppression (Putnam and Holt, 1983).

Research on winter covers that suppress pests could produce alternatives to methyl bromide fumigation. Although winter cover crops of rye and hairy vetch were the most consistent producers of biomass in a Florida study, no pest-suppressive effects were found and plant-parasitic nematode populations remained stable (McSorley and Dickson, 1989). Winter cover crops used by organic producers in California appear to be associated with enhanced soil biological activity and disease suppression (Workneh and van Bruggen, 1994). A follow up study documented enhanced soil microorganism activity and diversity supported by incorporating rye (Lundquist et al., 1999).

CONCLUSIONS

We report on some of the most promising cover crops for different spatial and temporal niches in the USA, documenting benefits such as soil-amelioration and promotion of healthy crops. Disincentives to growing cover crops include direct costs, indirect costs from management problems with some cover crops, and the economic opportunity cost of foregone income due to cash crop yield losses incurred from delayed planting, competition, or substitution by cover crops. There are significant niches within irrigated cropping systems where cover crops offer attractive benefits. Irrigation mitigates competition for water and provides economic incentives in the form of high value cash crops that respond to adoption of covers. Benefits of cover crops are not always found in short-term or factorial experiments as they involve long-term and cascading effects on crop and pest communities.

Managers need improved information about the effect of residue quality and quantity on microbiota and soil N and C pools so that informed decisions can be made about species choice, residue management, and timing of operations. Trade-offs are evident between cover crops that have tremendous potential to produce low quality biomass, for example grasses, and those that produce moderate amounts of higher quality residues, for example legumes. Legume bicultures are promising, where legumes are combined with C_4 grasses for warm zones, with C_3 grasses for cool zones, and with brassica for pest-control. Many farmers value such cover crops benefits, but cannot necessarily afford the initial investment. Future research should document more fully the magnitude of the environmental services that cover crops offer and their compatibility with current crop systems. If it can be shown that reduced erosion, reduced nitrate leaching, enhanced wildlife habitat, and other such ecosystems services benefit the nonfarm public, the case could be made to cost-share cover crop plantings under farm programs.

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