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Inter-relationships between crop type, management intensity and light transmissivity in annual crop systems and their effect on farmland plant diversity

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ABSTRACT

The recent boost of energy cropping in Central and Western Europe has greatly increased the demand for farmland leading to rapid land use change in many cultural landscapes. First-generation energy crops are now cultivated at more than 15% of Germany's arable land, but the consequences of this change in crop frequencies for agro-biodiversity are largely unknown. Concerns have been raised that this development might accelerate biodiversity loss due to high crop cover and reduced light availability in energy crop stands, which could further deteriorate the growing conditions for declining arable plant species. We analysed the transmissivity for photosynthetically active radiation (TPAR) in conventionally managed maize and oilseed rape fields (energy crops) and winter cereal fields (food/fodder crops) in Central Germany and contrasted it with TPAR measured in wheat fields managed according to agri-environmental schemes (AES). Secondly, we analysed the relation between light intensity and arable plant diversity metrics with respect to effects of field management and geographical differences. Light availability was lowest in maize stands (6% TPAR), followed by winter cereals and oilseed rape (10–13%). Field margins were brighter than field centres (17% vs. 10%). Highest light transmissivity was measured on AES fields (57%), which was associated with elevated plant diversity. Light availability explained a significant fraction of the variation in species richness also on conventionally managed field margins ($r^2 = 8\%$). Effects of light availability on community composition were found only when the least intensive systems (margins of conventional and AES wheat fields) were analysed. The main detrimental effect of the expansion of energy cropping on farmland habitat diversity is the loss of extensively managed farmland where light availability is higher. Reduced fertilizer use on conventional field margins will increase light availability and thus improve habitat conditions for arable plant species.

1. Introduction

During the last decade, new political frameworks for energy supply and agricultural production have led to large-scale changes in the relative frequency of major crop types grown in Western and Central Europe which fuelled the conversion of extensively managed fields, fallow land, pastures and meadows to intensively managed crop systems (Nitsch et al., 2012; Steinmann and Dobers, 2013). One major driver behind these changes are subsidies paid for the cultivation of energy crops (Charles et al., 2013; Khanna and Chen, 2013) which have been advocated by scientists and politicians as a tool to reduce CO_2 emissions for mitigating climate change (BMU and BMELV, 2010; IPCC, 2011).

Germany has declared particularly ambitious goals for replacing fossil fuels by renewable energies and the government pushes the transition by strong financial support (Britz and Delzeit, 2013). As a consequence, the area cultivated with energy crops in Germany tripled from less than 0.7 million ha in 2000 to ~2.1 million ha in 2012 equalling about 18% of the arable land (FNR, 2013a). This rapid expansion is currently mostly related to annual ('first-generation') energy crops (>90% of all energy crops grown on farmland) as these can be cultivated and handled with well-established, widely available machinery (FNR, 2013a,b). The

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two major energy crops in Germany are maize (*Zea mays* L.) and oilseed rape (*Brassica napus* L.) (FNR, 2013a,b). In 2012, maize for biogas production (representing 32% of the total maize acreage) was grown on approximately 7% of the arable land, and oilseed rape for biofuel and vegetable oil (representing 70% of the total rapeseed acreage) was grown on 8% of the arable land (Destatis, 2013; FNR, 2013a,b). Political strategies project that the proportion of land used for energy crop cultivation might increase up to 34% by 2020 (BMU and BMELV, 2010). This fundamental change in crop frequencies and land use intensity will also alter the environmental conditions determining the biodiversity in bioenergy landscapes.

Light is arguably the most important resource affecting the growth and survival of the arable flora. It determines photosynthetic carbon gain and regulates developmental processes such as seed dormancy, germination, and photomorphogenesis (Ballaré and Casal, 2000; Holt, 1995). Over a broad range of light intensities, productivity increases linearly with the amount of absorbed photosynthetically active radiation (PAR, 380–760 nm). While the low-input cropping systems of the past were characterised by relatively high light transmission through the crop, low light availability is likely an important limiting factor for arable plant growth and survival in the dark understory of modern crop stands (Kruk et al., 2006; Olsen et al., 2005). Reduced radiation transmission can alter the competitive ability of arable plants and crops (Bornkamm, 1961; Liu et al., 2009) and may affect other environmental factors, which vary with stand density and related radiation transmission, such as air humidity and air temperature in the stand interior.

Agricultural ecosystems are unique in the way that humans shape habitat conditions more strongly than in any other ecosystem (Ellenberg and Leuschner, 2010). More than climate and geological conditions, the choice of crop and the type of field management determine the light regime in crop stands (Ellenberg and Leuschner, 2010; van Elsen, 1994). The importance of light availability for the structure and composition of arable plant assemblages has already been emphasized by Rademacher (1939, 1950), but has led to only a few empirical investigations thereafter (e.g. Kruk et al., 2006; Liu et al., 2009; Olsen et al., 2005). Certainly, large-scale agricultural intensification and changes in crop rotations in many regions of Central and Western Europe in the last decades must have had profound effects on the light regime in and below crop stands at the field and landscape scale. In particular, concerns have been widely raised that light availability in maize stands is reduced as compared to other commonly grown crops, affecting farmland plant diversity. The sustainability of high-input maize production to fuel biogas plants has therefore been questioned. A diverse arable flora may not only help to halt erosion and reduce nitrate leaching, it is also an important food resource and/or breeding habitat for the pollinating and pest-controlling insects and birds of the agricultural landscape (Jordan and Vatovec, 2004; Marshall et al., 2003; Parish et al., 2009). The role of altered light conditions in explaining the large losses in farmland biodiversity during the past 50 years (e.g., Fried et al., 2009; Meyer et al., 2013; Storkey et al., 2012; Sutcliffe and Kay, 2000) has not yet been quantified and its relative importance with respect to other chemical and mechanic stressors in modern cropping systems remains unknown.

Previous PAR measurements in modern crop stands were primarily done for the purpose of parameterizing of crop growth and yield models (Daughtry et al., 1992; Gallo et al., 1985; Hipps, 1983), but did not deal with weed growth conditions. Our study for the first time links light measurements in modern high-yield crop stands to the weed vegetation using a systematic, replicated sampling design. We did this in regular cropland used for food, fodder or energy production and did not study experimental stands. Apart from a few exemplary measurements (van Elsen, 1994), such an approach has not been adopted before. This will allow drawing conclusions on the influence of changes in crop rotations on the light regime in crop stands and on weed growth conditions on the landscape level.

We addressed the following questions: (1) How does the light regime at ground level, expressed as PAR transmissivity (TPAR), vary between cropping systems? (2) Which spatial scale of observation contributes most to the variation in light conditions? (3) How much of the variation in TPAR in arable fields can be explained by crop performance (crop cover), management (choice of crop, conventional vs. AES cropping) and/or regional effects? (4) How does TPAR relate to the structure and composition of arable plant assemblages (weed cover, species richness and community composition) in different cropping systems in comparison to other explanatory factors such as field management and study region?

2. Methods

2.1. Study area

The fields investigated were selected in two regions in the central uplands of Germany, which are characterized by a hilly countryside with plains highly suitable for productive arable farming (Fig. 1). The first study region, the Lower Saxon hills (LS), is situated in the county of Göttingen (1118 km^2; elevation 104–579 m a.s.l.). Mean annual precipitation is 650 mm and mean annual temperature 8.7 °C (DWD, 2013). The second study region is located in the agricultural plains of the Thuringian Basin (TB; 1058 km^2; 134–413 m a.s.l.). The climate in the Thuringian Basin is drier (mean annual precipitation: 500–550 mm) and slightly warmer (mean annual temperature: 9.2 °C) than in the Lower Saxon hills (DWD, 2013). Due to differences in agricultural policies on both sides of the inner German border before 1990, the agricultural landscapes in the two study regions differ structurally. The proportion of farmland is higher in the Thuringian Basin than in the Lower Saxon hills (78% vs. 44%, respectively) and fields are on average larger [average size of an administrative field unit 18.8 ha (TB) vs. 6.6 ha (LS)].

2.2. Sampling design

A total of 50 arable fields, equally distributed across both regions, were selected for vegetation surveys, which were conducted in the summers of 2011 and 2012. In each region, five fields of four different crops (maize, oilseed rape, winter barley and winter wheat) under conventional management (i.e. application of fertilizers and herbicides according to common agricultural practice) were selected. We included only fields with a closed crop stand without any signs of crop growth failure. We did not distinguish between fields on which maize or oilseed rape was specifically grown for the purpose of energy production and fields where these crops were cultivated for food/fodder production. Interviews with farmers and energy plant operators, consultation of the agricultural literature (Lütke-Entrup and Schäfer, 2011) and earlier analyses of available field management data for 28 maize fields (Seifert et al., unpublished data) revealed no differences in fertilizer application or weed management between these two types of product usage. As far as oilseed rape is concerned, farmers are often not even aware of what their product is finally going to be used for by the purchaser. Impacts of energy cropping on biodiversity were thus assumed to arise exclusively from changes in the relative frequency of the crops in time and space and from the conversion of extensively managed fields, fallows, pastures and meadows to intensively managed arable land. Additionally, five winter wheat fields, which were managed according to an