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Insect- and spider-friendly mowing technology in grassland – overview and evaluation

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Meadows and pastures (grassland) are man-made agricultural areas that are managed intensively to extensively. In Germany, about one third of these areas is permanent grassland. Depending on the intensity and form of use, permanent grassland represents important habitat for many plant and animal species and can decisively contribute to the preservation of biological diversity. In this review, we pay particular attention to mowing and its effects on arthropods, an ecologically highly relevant group. Mowing contributes indirectly through various factors to the general decline of arthropods but also has a direct effect by killing arthropods in the mower. We have reviewed various mowers from a technical perspective and evaluated their effect on the arthropod fauna in grassland. In addition, we present existing arthropod-friendly alternatives to conventional mowing technology and discuss their potential. Scientific studies show that, irrespective of the studied arthropod group, bar mowers and, especially, double-blade bar mowers cause less mortality than rotary mowers. The highest damage rates have been found with conditioners and flail mowers. The consistent use of insect flushing bars and modified rotary mowers might contribute to a reduction in arthropod mortality with only minor economic losses.

Keywords

Insect-friendly mowing, insect decline, agricultural grassland use, mowing technology

Until the late 1990s, only sparse literature was available concerning the effects of various mowing equipment on grassland fauna and their tractor-induced damage (Tyler et al. 1998, Oppermann and Classen 1998). During the following years, the importance of grassland for the conservation and promotion of biodiversity became more apparent (Oppermann and Classen 1998, Humbert et al. 2010c). Several studies aimed at determining the losses of grassland fauna and at developing practical recommendations for the protection of the flora and fauna were therefore carried out in order to clarify previous uncertainties about mowing-related damage, especially with regard to insects (Fluri et al. 2000, Oppermann and Krismann 2001, Vickery et al. 2001, Robinson and Sutherland 2002, Humbert et al. 2009, Humbert et al. 2010c). In Germany, where permanent grassland accounts for approx. 28.5 % (as of 2020, German Environment Agency 2021) of agricultural land, the practical implementation of animal-friendly mowing is a challenge. However, grassland such as meadow orchards or meager dry grasslands are, because of their structural diversity and staggered flowering sequences, particularly valuable man-made habitats for many bird species, amphibians, and invertebrates such as spiders and insects (van de Poel and Zehm 2014). The latter have attracted much attention during the last few years mainly because of the studies of Hallmann et al. (2017) and Seibold

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et al. (2019), both having pointed out the massive decline in the numbers of species and individuals in these groups. Several investigations have provided evidence that a large proportion of arthropods living in agricultural grassland are directly injured and/or killed during mowing (e.g. Oppermann and Krismann 2001, Humbert et al. 2010c, Betz et al. 2022, Steidle et al. 2022). In addition, research is increasingly showing indirect consequences caused, for example, by high mowing intensity (Tscharntke et al. 2021, Blüthgen et al. 2022).

Here, we review the current state of nature- and arthropod-friendly mowing techniques and show the associated challenges and perspectives. We pay particular attention to the evaluation and validation of insect- and spider-friendly mowing technology. The central question is whether the biodiversity and preservation of intact grassland ecosystems can be achieved by using effective mowing technology.

We have taken information concerning the principles of the various mowing techniques from technical articles and current textbooks. Further information on current mowing techniques has been retrieved from publicly available product manuals from the relevant manufacturing companies. Few scientifically published data are available about the direct damage of arthropods caused by the various mowing techniques, and any publications are difficult to compare. Therefore, not only articles published in peer-reviewed scientific journals, but also theses at universities, newspaper articles or online reports, book contributions, reports of governmental agencies, and patents were considered in this review.

Overview of mowing techniques used today

Fundamentals of selected mowing techniques

Two different cutting principles are used in practice for mowing grassland, whereby a distinction is made between shear cut and impact cut (Fehr et al. 2016). In shear cut, the grass is guided and cut along either a fixed counter-blade (finger cutter bar mower) or a moving counter-blade (double-blade mower, Eichhorn 1999). In both designs, the blades move in an oscillating manner. An average relative speed of at least 2.5 m s^{-1} between the blade and the counter-blade is necessary to ensure a clean cut (Schaefer 1966). In grassland management, oscillating mowers with shear cut have played only a minor role for decades (Claus 1988). The reasons for this are the higher maintenance costs attributable to the wear of the blades, the high susceptibility to failure, and the high total costs (including labor costs per hectare), which are approximately twice that of rotary mowers commonly used today (Schön 1998, Saurma-Jeltsch et al. 2020). Despite these disadvantages, double-blade mowers are the focus of environmentally friendly mowing technology, as scientific studies have established their lower damage rates compared with those of rotary mowers (see section: Effects of varoius mowing techniques on insects and spiders).

The rotary mowers commonly used today cut the grass with an impact cut (Claus 1988, Schön 1998, Eichhorn 1999), which, in contrast to shear cut, does not involve a counter blade. This requires cutting speeds of approx. 80 m s^{-1} to be able to use the inertial and bending forces of the stalk as counterforces for the cut (Kemper et al. 2014). Compared with oscillating mowers, rotary mowers are characterized by a higher working speed and greater performance (Schön 1998). Rotary mowers are differentiated according to the position of the rotation axis and the drive. Top-driven drum mowers and bottom-driven disc mowers have a vertical axis of rotation. Flail mowers, on the other hand, are usually driven from the side and have a horizontal axis of rotation transverse to the direction of travel. Rotary lawn mowers, which are rarely used in agricultural grassland and usually have only one blade rotating around the vertical axis, are not considered further here. In agriculture, mowers are mainly used for forage harvesting, whereby the crop is cut and left lying on the ground, for which double-blade, disc, and drum mowers are well suited. In municipal applications, on the other hand, the crop is often shredded further after cutting; this is the reason that flail mowers, designed for shredding, are mainly used in this sector.

Bar mowers

Oscillating mowers such as the finger cutter bar or double-blade bar are characterized, among other aspects, by a clean cut, low power requirement, and light construction (Schön 1998, Fehr et al. 2016). In grassland mowing, double-blade mowers are preferred (Eichhorn 1999) in which both the blade and the counter-blade are in motion. This leads to a better mass balance than with the finger cutter bar mower in which only the blade moves. As a result, higher blade speeds are possible on the double-blade mower, which in turn allows higher working speeds (Meiners et al. 2009a). In addition, the two moving blades of the double-blade mower are better able to eject stones coming into contact with them than is the blade of the finger cutter bar mower in which stones are more likely to be trapped and cause the blade to jam (Meiners et al. 2009a).

Rotary mowers – disc mowers

Rotary mowers are superior to double-blade mowers in terms of susceptibility to failure. This advantage is mainly attributable to the brackets in which the rotary blades are movably mounted. The blades can thus avoid obstacles to a limited extent (Schön 1998). However, rotary mowers have a higher weight and a greater power requirement compared with bar mowers (Schön 1998), because the mower discs must rotate at high speed to achieve the blade speeds of up to 80 m s^{-1} needed for impact cutting. For example, a mower disc diameter of 500 mm requires a disc rotation of approximately 50 s^{-1} to achieve a speed of 80 m s^{-1} on the outer edges of the blades. Since a modern mower disc has two blades mounted opposite to each other, the frequency at which one of the two blades cuts grass at any point on the "orbit" in the present example is 100 s^{-1}. In the overlapping zones, where the cutting areas of the two mowing discs coincide, the cutting frequency is doubled to 200 s^{-1} (Figure 1). High cutting frequencies therefore lead to multiple cuts of the grass. The cutter bar of a disc mower glides over the surface on skids, relieved of weight by a suspension system (Fehr et al. 2016, Hensel 2019). The cutting height is changed via the inclination of the cutter bar or the attachment of special skids (Hensel 2019).

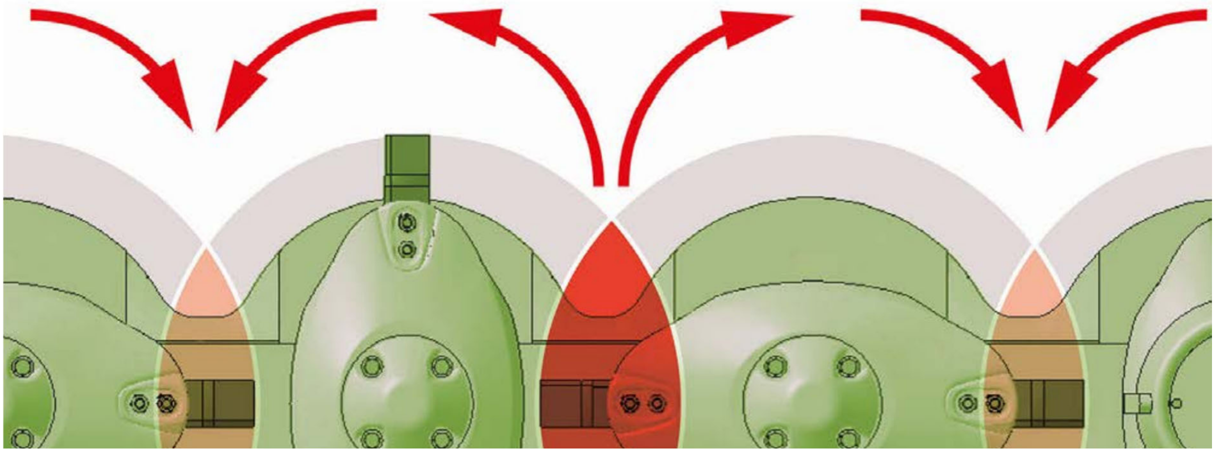

Figure 1: Top view of the overlapping zones of the KRONE EasyCut cutterbar; red arrows show the direction of rotation of the discs, orange zone = overlapping area where the blades move backward and red area = overlapping area where the blades move forward (Maschinenfabrik Bernhard Krone GmbH & Co. KG 2022)

Conditioners on rotary mowers

Conditioners can be fitted to both drum and disc mowers. The function of the conditioner is to bend, crush, and splice the grass, thereby damaging the stabilizing and evaporation-inhibiting wax layer (cuticle) of the plant's outer surface and accelerating the outflow of water (Dernedde 1969, Schön 1998, Eichhorn 1999). As a result, the mown grass dries faster, and the harvesting process is shortened (Dernedde 1969). In rotary mowers, the conditioner is mounted behind the cutter bar and takes over the crop directly after the cut. Various types of conditioners are used depending on the composition of the stand.

The use of a tine conditioner is recommended for grassland stands with a high proportion of stalks (Schön 1998, Claas Vertriebsgesellschaft mbH 2022, Maschinenfabrik Bernhard Krone GmbH & Co. KG 2022). This type of conditioner consists of a tine rotor that guides the mown grass past a friction plate or several counter-blades. In this process, the stalks are bent, spliced, and struck. The intensity of the processing can be adjusted by the position of the friction plate or the counter-knives and by the speed of the rotor. For leafy crops with a high proportion of clover or legumes, roller conditioners are used (Schön 1998, Claas Vertriebsgesellschaft mbH 2022, Maschinenfabrik Bernhard Krone GmbH & Co. KG 2022). The mown crop is passed between two profiled rollers and crushed. The intensity of the conditioning can be adjusted by the distance between the rollers. This type of processing is gentler on the material, as the separation of individual plant parts is avoided (Maschinenfabrik Bernhard Krone GmbH & Co. KG 2022).

Rotary mowers – Flail mowers

Flail mowers and mulchers differ in the way that they work from disc and bar mowers. The latter mowers cut the grass and leave it on the ground, so that only the stalk is cut off and the grass is not shredded further. The influence of the blades here remains limited to the cutting horizon, which roughly corresponds to the thickness of the blades (Schön 1998). A flail mower, on the other hand, is designed to shred, strike, and crush all the vegetation several times. To do this, a horizontal shaft equipped with blades or flails rotates at a speed of up to 38.34 s^{-1} (Rux 1999), and the blades, which are freely suspended from the shaft, can reach a linear speed of 45 to 65 m s^{-1} (Kuhn Maschinen-Vertrieb Gmbh 2021). The rotation of the shaft is mostly against the direction of travel. Because of the geometry of the machinery, a sufficiently high crop is first cut by a blade at the height of the shaft. Depending on the crop and the cutting height, the first contact can also take place later, as plant parts lying below the shaft are only gradually cut off during the pass. The rotational movement of the blades or flails carries the cut material above or below the shaft and finally deposits it behind the rotor over the entire working width. On its way over the shaft, contact with the cover of the rotor leads to further processing of the green material (Rux 1999). The removed plant material usually remains on the area as mulch for fertilization. A suction mower sucks up the mown material after the shredding step. The free suspension of the blades means that they are deflected on contact with an obstacle, making the flail mower insensitive to impacts and any hard resistance. Flail mowers are therefore particularly suitable for mowing fallow land and roadside verges (Meiners et al. 2009b). Height guidance and cutting height adjustment are carried out via support wheels, skids, or support rollers (Meyer 1998).

Theoretical calculations to compare the potential harmful effects of various mowing techniques on arthropods

The functional principles of double-blade, disc, and flail mowers result in a variety of theoretical risk potentials for insects and other arthropods. To determine risk potential, the area that is swept or affected by the blades of a mower per second is calculated. The risk potential for the arthropod fauna increases with the size of the swept area. The mowers are viewed from above, so that only the movement of the blades projected onto the ground is determined and not the volume traversed by the blades. To determine the damage potential, only the area swept (per unit of time) by the blades is relevant; the movement of the supporting parts is not considered.

First, the affected area A_E is calculated (Table 1). It describes the area swept by a blade during one revolution or stroke. Area A_E is then multiplied by the number of blades present in the respective mower for the processing of a working width of 3.05 m. The determination of the area swept per second is based on the rotation speed or stroke frequency required by the respective mower. All the machines presented here have been selected as being exemplary of their design. The calculations for the double-blade mower are based on data from Schön (1998) and the ESM System Bidux (Kersten Maschinenfabrik 2022). The double-blade mower has a section pattern of 84 mm on the upper and lower blades. To achieve approximately the required working width of 3.05 m, 36 blades each are needed at the top and bottom. The working width in this case is 3.024 m. One blade is 60 mm long. In the case of the double-blade mower, the affected area A_E results from the lateral displacement of a blade by the stroke and from the length of the blade (Figure 2). The values for the disc mower have been determined on a Novacat 305 h from Pöttinger (Alois Pöttinger Maschinenfabrik GmbH 2007; Figure 2), available at the Institute of Agricultural Engineering at the University of Hohenheim. The influenced area A_E here is the circular “orbit” of a blade above the ground. The mower has a working width of 3.05 m, which is achieved by seven partially overlapping mowing discs.

Table 1: Calculation of the swept area per second as a measure of the potential threat to small animal fauna in grassland for three different mower types: double-blade, disc, and flail mowers. The affected area A_E per stroke or rotation is calculated from the stroke or rotation frequency of the respective mower type to the affected area per second. This area is then divided by the area mown by the mower per second. The ratio of the area affected by the blades per second to the area mown by the mower per second is also presented (N/A = not applicable).

	Double-blade mower (Figure 2a)	**Disc mower (Figure 2b)**	**Flail mower (Figure 2c)**
Working width	3,024 mm	3,050 mm	3,050 mm
Cutting width of one blade	60 mm	50 mm	115 mm
Rotor diameter incl. flails/blades	N/A	520 mm	650 mm
Stroke	42 mm	N/A	N/A
Affected area A_E per stroke or rotation	0.0025 m^2	0.0738 m^2	0.0748 m^2
Number of blades or flails	72	14	34
Rotation speed	N/A	50 1/s	28.34 1/s
Single stroke frequency	50 s^{-1}	N/A	N/A
Affected area per second	9.072 m^2 s^{-1}	51.653 m^2 s^{-1}	72.009 m^2 s^{-1}
Driving speed	2.22 m s^{-1}	3.33 m s^{-1}	2.22 m s^{-1}
Area mown by the mower per second at correspon-ding driving speed	6.713 m^2 s^{-1}	10.157 m^2 s^{-1}	6.771 m^2 s^{-1}
Ratio of affected area per second (blades) to mown area per second (working width)	1.351	5.085	10.635

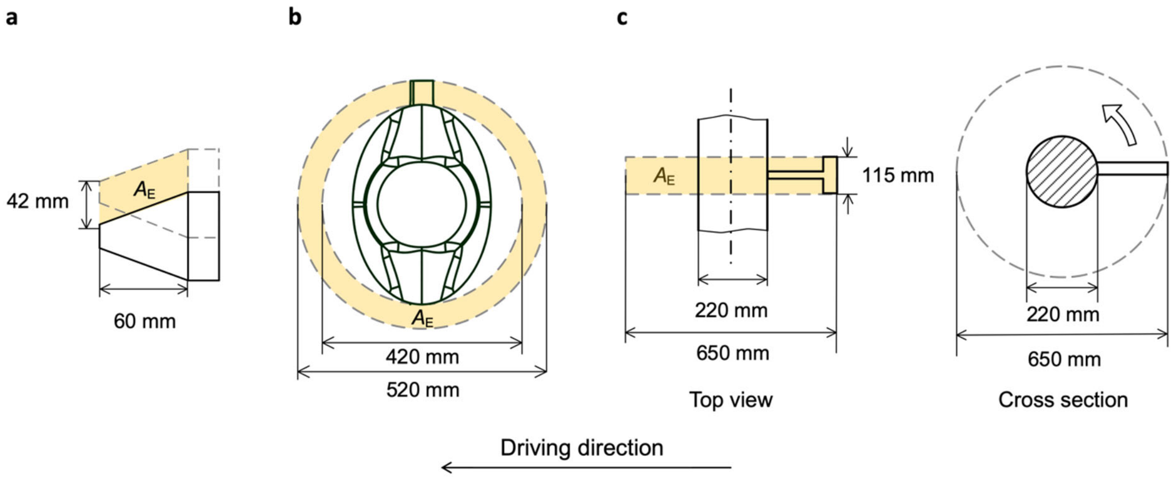

Figure 2: Top view of a) a double-blade mower and b) a disc mower, plus the top view and cross-section of c) a flail mower with the area AE marked in yellow, which is influenced by the blade during a stroke or a revolution

The data for the flail mower is based on an RM series implement from Kuhn (Kuhn Maschinen-Vertrieb GmbH 2021). Flail mowers are offered in working widths of 2.80 m (with 32 flails) or 3.20 m (with 36 flails). Thirty-four flails are needed to adjust the working width to the desired 3.05 m. In flail mowers, the affected area A_E describes the area that a flail sweeps over on the ground when the rotational movement is viewed from above. The area A_E is therefore composed of the diameter of the rotor including the flails and the working width of a single flail (Figure 2). The area A_E describes the maximum possible influenced area, which is only achieved when the crop has grown to the height of the rotating shaft. With lower stands, the affected area is correspondingly smaller.

The blade of the double-blade mower covers a considerably smaller area A_E per stroke than the blades of the two rotary mowers per revolution. The area A_E is then multiplied by the number of blades required and by the rotational frequency or stroke frequency of the blades to obtain the affected area per second. Schaefer (1966) has reported a double stroke frequency of 25 s^{-1} for the blades of a double blade bar. One double stroke corresponds to the forward and backward movement of a blade. For the calculation of the area swept per second, this frequency is converted to the single stroke, i. e., it corresponds to 50 s^{-1}. The area swept per second by the blades of the double-blade mower is 9 m^2, which is significantly smaller than that of the disc mower with 52 m^2 or the flail mower with 72 m^2, as the latter moves more blades at higher speeds.

A mower with a working width of 3.05 m for discs and flail mowers and 3.024 m for double-blade mower sweeps an area dependent on the driving speed per second. This area describes the area actually mown or worked and can be related to the area swept by the blades in one second. This ratio indicates how much larger the area covered by the blades per second is than the area mown by the mower in the same time. The area mown by the mower per second is 7 m^2/s for the double-blade and flail mower and 10 m^2/s for the disc mower. Finally, the ratio of the area worked per second to the area affected by the blades per second is calculated. For the double-blade mower, the ratio is 1.3, which means that the blades of the mower sweep only slightly more area per second than is mown by the mower per second. For the disc mower, the area swept by the blades per second is approximately five times greater and, for the flail mower, the area is ten times greater than the area worked or mown by the double-blade mower. The double-blade mower therefore appears to be the least damaging mower for arthropods such as insects, as the movement of the blades above the ground is comparatively small.

However, this comparison neglects several parameters that can have a considerable influence on arthropods in practice. On the one hand, the crop flow in the machine after cutting is not taken into account. For example, the crop is cut and chopped many more times in the flail mower. On the other hand, rotating mowers develop a suction, because of the high rotational speeds, and this can actively suck arthropods into the blades. The model presented here should therefore be understood primarily as an approximation showing the ways in which various potential hazards for insects and spiders result from the design differences of the mower types. A final assessment of the harmful effect on arthropods is not possible with the models presented and can only be achieved in field trials.

Effects of various mowing techniques on insects and spiders – documented damage

In our literature search, we have been able to identify several studies dealing with the effects of various mowing techniques, the entire harvesting process, and the associated damage to insects and spiders. To emphasize the importance of arthropod-friendly mowing techniques, we provide an overview of the results on some fundamental studies on the mowing-related damage rate of various arthropod groups.

Depending on the study, damage rates refer to the proportion of individuals (or model bodies) injured or killed by mowing compared with the number of individuals thought to be within the studied area (Hemmann et al. 1987, Wilke 1992, Löbbert 2001, Oppermann and Krismann 2001, Humbert et al. 2010a, Humbert et al. 2010b, Betz et al. 2022, Steidle et al. 2022) or to the proportion of injured compared with non-injured arthropods in the mown grass (Fluri et al. 2000, Hecker et al. 2022). The indirect negative consequences of mowing, such as microclimatic changes are not considered. The evaluation of the existing literature and the development of resulting recommendations is associated with certain challenges. Most of the studies differ in terms of the mowing techniques and arthropod groups studied and of the methodological approach used to determine damage to arthropods. This makes it difficult to compare the studies but, at the same time, represents a broad spectrum. In addition, most studies have not been performed with a sufficiently high number of replicates, and standardized long-term studies on defined areas are lacking. In addition, ecological studies are generally subject to many unknowns, such as weather effects or seasonal fluctuations in population densities of arthropods (Humbert et al. 2009, van de Poel and Zehm 2014).

The first study to determine damage rates for various mowing techniques was carried out in the 1980s (Hemmann et al. 1987) and involved the testing of the damaging effects of a bar mower, a flail mower, and a suction mower on true bugs and mealworm beetles. The insects were applied to 3 x 2.7 m experimental plots for 5-10 minutes before mowing and those remaining were counted immediately after mowing. Different damage rates were observed depending on the insect group (adult bugs, bug larvae, and mealworm beetles). Overall, the proportion of killed or injured individuals was lowest for the bar mower with an average of 28.4 %, whereas the damage rates of the suction mower with an average of 46.5 % and the flail mower with an average of 62.8 % were significantly higher. For adult bugs, the negative effects of both mowing techniques were highest, with 84–88 % of individuals being killed or injured (Table 2).

Table 2: Summary of literature review concerning the percentage of mowing-related damage rates of various insect groups and spiders when mowing with various mowers: B = bar mower, C = conditioner, R = rotary mower.

	Damage rate in %						
Insect and spider groups	**Bar mower**	**Rotary mower**	**Rotary mower with conditioner**	**Flail mower**	**Suction Mower**	**Entire harvesting process**	**Publication**
Orthoptera							
Diverse species	6	30					Wilke (1992)
Diverse species						75	(Kiel 1999), citeted in Humbert et al. (2009)
Diverse species	9	21	34			80	Oppermann and Krismann (2001)
Metrioptera bicolor						42	Wagner (2004)
Chorthippus parallelus		59					Gardiner (2006)
Diverse species (nymphs)		21					Gardiner (2006)

Insect and spider groups	Bar mower	Rotary mower	Rotary mower with conditioner	Flail mower	Suction Mower	Entire harvesting process	Publication
	Damage rate in %						
Diverse species	13	21	57			66 (B) – 84 (R+A)	Humbert et al. (2010a)
Beetles (Coleoptera)							
Tenebrio molitor	16			60	30		Hemmann et al. (1987)
Epicauta occidentalis	4		21				Blodgett et al. (1995)
True Bugs (Heteroptera)							
Dysdercus intermedius; adults	52			88	84		Hemmann et al. (1987)
Dysdercus intermedius; nymphs	17			41	26		Hemmann et al. (1987)
Diverse species				29			Steidle et al. (2022)
Butterflies (Lepidoptera)							
Helicoverpa armigera; caterpillars	18	16		77			(Löbbert et al. 1994), cited in Humbert et al. (2009)
Pieris brassicae; caterpillars	20	37	69				Humbert et al. (2010b)
Hympenoptera							
Honey bee (*Apis mellifera*)		5	35				Fluri et al. (2000)
Diverse species				55			Steidle et al. (2022)
Other							
Diverse cicada species (Cicadina)				48			Steidle et al. (2022)
Diverse spider species (Araneae)				49			Steidle et al. (2022)
Diverse insect and spider species	25	25			33		Kraut (1995)
Diverse insect and spider species		52	70				Hecker et al. (2022)
Diverse fly species (Diptera)				59			Steidle et al. (2022)
Larvae of various holometabolous insects				73			Steidle et al. (2022)
Wax models							
Wax model (spiders/carabids)	4	12			55		(Löbbert et al. 1994), zitiert in Humbert et al. (2009)
Wax model (caterpillars)	11	17	28				Humbert et al. (2010b)

Table continued on next page

Löbbert (2001) also compared various flail mowers with a disc and a double-blade mower. Here, however, instead of living arthropods, model bodies with the physical properties of carabid beetles or spiders were applied to the vegetation on the ground, at the cutting height (5 or 10 cm), or at a height of 20 cm. Similarly to Hemmann et al. (1987), the least damage was determined for the bar mower. At a cutting height of 10 cm, some of the damage rates were even less than 10 %. The disc mower damaged approximately 30 % of the model bodies, whereas the various flail mowers showed damage rates ranging from 50 to over 90 % depending on the application height and the model body used (Table 2).

Several studies investigated the effects of bar mowers and rotary mowers on grasshoppers. Wilke (1992) reported damage rates of only 6 % when a double-blade mower was used, whereas the tested rotary mowers killed 28–30 % of the grasshoppers (Figure 3). Similar results were obtained by Oppermann and Krismann (2001). The bar mower was found to be gentler on grasshoppers with only 9 % damage, whereas employment of a rotary mower killed 21 % of the grasshoppers. The additional use of a conditioner increased the losses to 34 % (Table 2). A study of honey bees by Fluri et al. (2000) provided similar results (Table 2). Mowing with a rotary mower without a conditioner only killed or injured 5 % of the honeybees, whereas 35 % were killed when a conditioner was employed. Extrapolated to one hectare of flowering meadow, this would have resulted in losses of 2,000 honeybees without conditioner and 9,000 to 25,000 with conditioner.

Figure 3: Large marsh grasshopper *Stethophyma grossum* damaged by mowing with a rotary mower (© T. Kimmich).

The effects of conditioners on a wide variety of arthropod groups were investigated in a study by Hecker et al. (2022): 70 % of the arthropods contained in the mown material were damaged (bruised thorax or abdomen) after mowing with a rotary mower plus conditioner, whereas only 52 % of the individuals in the mown material from plots mown without conditioner showed such damage (Hecker et al. 2022). So far the most extensive studies concerning mowing and insect fauna have been carried out by Agroscope (Humbert et al. 2010b, Humbert et al. 2010a; Table 2). In addition to bar, drum, and disc mowers, the effects of a conditioner were tested on living insects (grasshoppers and butterfly caterpillars) and on wax models of various sizes. The hand-operated bar mower showed damage ranging from an average of about 11 % for the wax models to about 20 % for the caterpillars (Humbert et al. 2010b). Mowing with the drum mower damaged an average of 17.2 % of the wax models and killed about 40 % of the caterpillars depending on their position in the vegetation. The use of an additional conditioner increased this mortality to 70 % (Humbert et al. 2010b). The bar mower was also the gentlest mower on grasshoppers, with 13 % killed. A conditioner on the drum mower increased damage rates significantly from 21 % to an average of 57 % (Humbert et al. 2010a). Grasshopper damage rates were recorded for the hay harvesting processes of tedding, raking, baling, and loading that occur after mowing. This resulted in mortalities of on average 27 % attributable to tedding and baling and up to 51 % attributable to tedding and raking together (Humbert et al. 2010a). Depending on the mower, the total mortality rates calculated for the entire harvesting process were on average 66 % for the bar mower and 84 % for the drum mower with conditioner (Table 2, Figure 4). However, this work suggests that the processes following mowing can cause higher levels of damage than the mowing itself (Humbert et al. 2010a).

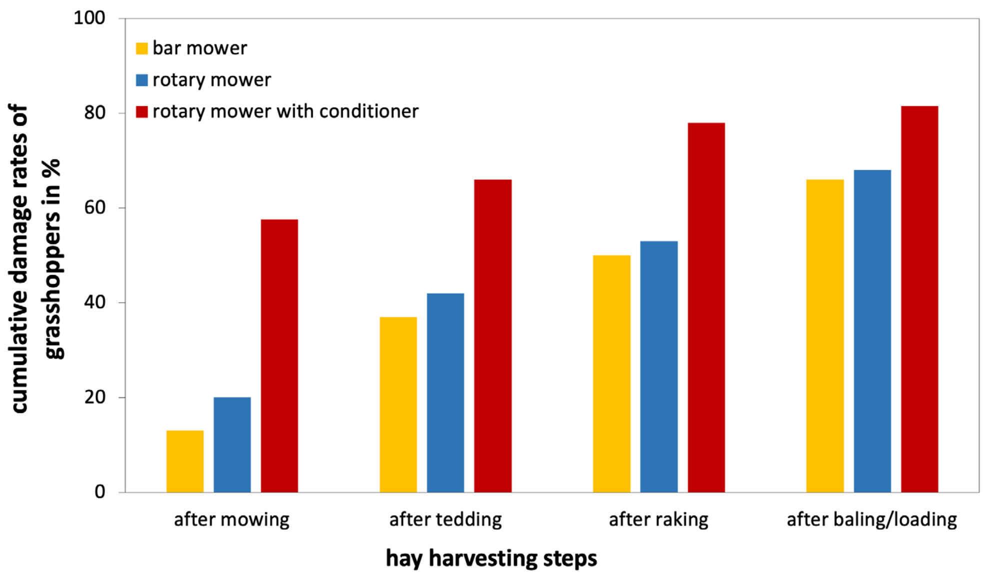

Figure 4: Cumulative percentage damage rates of grasshoppers in grassland after various harvesting steps with various types of mowing equipment. The values for the entire harvesting process were calculated form individual survival rates of the respective steps (Humbert et al. 2010a) and subsequently converted into damage rates.

Further arthropod groups, which had not or were only rarely investigated with regard to mowing losses, were included in a study on the influence of a conventional flail mower for municipal use (Betz et al. 2022, Steidle et al. 2022). Damage rates of up to 73 % were found, depending on the group (Table 2).

Insect groups affected by mowing

Grassland ecosystems created by human management provide important habitat for many insects and other arthropods (van de Poel and Zehm 2014, Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2015, Kremer 2020). The most famous flower-visiting groups include bees and wasps (Hymenoptera, Figure 5a), flies (Diptera, Figure 5b), and butterflies (Lepidoptera, Figure 5c). Many of these representatives have developmental stages that are not very mobile (e.g., butterfly caterpillars and larvae sawflies) and are therefore particularly vulnerable to mowing (Fluri et al. 2000, Betz et al. 2022, Steidle et al. 2022). Various beetle species are also found on grassland as flower visitors, herbivores, or predators, such as *Trichodes alvearius* (Fabricius 1972, Coleoptera,

Figure 5d; Willner 2013). To date, grasshoppers (Orthoptera, Figure 5e) have received the most attention with regard to damage caused by grassland mowing (Oppermann and Krismann 2001, Wagner 2004, Gardiner 2006, Humbert et al. 2010a). Not only direct damage during mowing, but also losses attributable to microclimatic changes caused by mowing are well documented for grasshoppers (Gardiner and Hassall 2009). The sap-sucking true bugs and cicadas (Hemiptera, Figure 5f) are also inhabitants of or visitors to grassland and are therefore affected by frequent mowing (Hemmann et al. 1987, Steidle et al. 2022).

Figure 5: Selected representatives of well-known insect groups: a) Bumblebee (*Bombus sp.*, Hymenoptera) collecting pollen, b) Large bee-fly (*Bombylius major*, Diptera) on creeping buttercup (*Ranunculus repens*), c) Imago and caterpillar of *Papilio machaon* (Lepidoptera), d) *Trichodes alvearius* (Coleoptera), e) Grasshopper nymph (*Chorthippus sp.*, Orthoptera), f) Striped bug (*Graphosoma italicum*, Heteroptera), a) – d) © Lea von Berg, e) – f) © Florian Weber

"Arthropod-friendly" mowing technology

Although the damaging effects of mowing on arthropods, as shown above, is known, few attempts have been made to avoid this effect by developing alternative techniques. Even those limited approaches undertaken provide hardly any accompanying ecological studies that establish their effectiveness. To date, only modern double-blade bar mowers or insect flushing bars mounted in front of the mower represent gentle alternatives for the agricultural management of grassland (Zieger 2021). The Naturschutzbund Deutschland e.V. (NABU) in Gärtringen-Nufringen (Baden-Württemberg), for example, used a bracket mounted in front of the mower as an insect flushing bar to encourage insects and other arthropods to escape, when managing ecologically valuable grassland areas (Hotz 2013). A unpublished accompanying study has confirmed this effect (Oppermann et al. 2012). Increased political and public interest in arthropod conservation and biodiversity preservation in recent years has led a number of companies to develop and incorporate variants of what is believed to be the first insect flushing bars, such as drooping tines, chains, and tarpaulin, into their mowers (Meissner 2020, Zieger 2021). An alternative form of insect flushing bar has been developed by Fischer Maschinenbau GmbH & Co KG. In their EcoCut, arthropods will be gently removed from the vegetation with a horizontal blower set at an air speed of 150 to 260 m/s and fixed in front of the mower unit (according to the patent). A so-called "honeycomb test" has shown a protective effect of up to over 90 % with their method (Beutel and Reber 2020, Meyer 2020). This superficially sounding promising approach, however, appears to be scientifically unsound, since the "honeycomb test" only investigates the effect on honeybees on honeycombs. The effect that the flushing bar has on wild arthropods in natural vegetation thus cannot be estimated based on this method.

A promising type of arthropod-friendly mowing technology has been developed by MULAG Fahrzeugwerk (Heinz Wössner GmbH & Co. KG) and introduced to the market in form of the ECO 1200 embankment mower for roadside mowing. The key innovation of this mowing head is a modified airflow and a largely closed base that prevents arthropods from being sucked into the mowing head and thus reduces arthropod losses (Meissner 2020). In addition, the mowing head has an adjustable insect flushing bar made from truck tarpaulin, an increased cutting height from 10 to 15 cm, narrow blades, and a very narrow contact surface to the ground. Ecologists have compared the ECO 1200 with the conventional MK 1200 flail mowing head from the same company. Depending on the arthropod group, the MK 1200 causes mowing losses ranging from 29 to 73 % (Table 2). Use of the ECO 1200 resulted in no significant mowing losses for spiders, true bugs, cicadas, and holometabolous larvae between unmown control meadow and meadow mowed with the ECO 1200 (Betz et al. 2022, Steidle et al. 2022). In comparison with the conventional MK 1200, for flies and hymenopterans, the damage rate decreases from 59 and 55 % to 34 and 40 %, respectively (Betz et al. 2022, Steidle et al. 2022). Thus, the ECO 1200 represents an arthropod-friendly alternative for roadside mowing, despite the involvement of the rotary mowing technique. Other mowers equipped with a wide variety of modifications or scarecrows are available primarily for municipal use (Zieger 2021). However, no proof has been provided for their effectiveness.

Conclusions

Meadow management by mowing is essential to maintain the meadow ecosystem, this being the only method to guarantee that such an area remains permanently open (Humbert et al. 2010c, Kremer 2020). At the same time, this type of management poses a threat to in meadow-living larger vertebrates and invertebrates such as insects and spiders (Humbert et al. 2010c, Seibold et al. 2019). Differences in the extent of arthropod losses during mowing can be explained by the different construction or general functioning of the various mowing technologies (Table 1). The circular "orbits" of the blades and the high speeds of disc and flail mowers result in a large portion of the managed area encountering the blades. Thus, disc or flail mowers cover a four to six times greater area per second than a bar mower with the same working width (Table 1). The probability that arthropods will be injured or killed when a rotary mower is used is therefore significantly higher than when a bar mower is employed. Additionally, the potential damaging effects of rotary mowers are increased by the use of conditioners and by the suction that can draw arthropods from the ground into the blades.

The potential damage to insects and spiders based on the construction and operation of individual mowers has been confirmed by several studies (Hemmann et al. 1987, Fluri et al. 2000, Löbbert 2001, Oppermann and Krismann 2001, Humbert et al. 2010a). In addition, the grass-harvesting processes that occur immediately after mowing can also result in high losses (Humbert et al. 2010a; Table 2, Figure 4). The use of modern double-blade mowers and the installation of insect flushing bars should reduce the damaging effect of mowing on meadow-dwelling arthropods (Oppermann et al. 2012, Hotz 2013, Bb-Umwelttechnik GmbH 2022). Mowing with rotary mowers can be made more arthropod-friendly by the use of modified mowers that have a lower suction effect and thus a high potential to reduce or eliminate mowing losses (Betz et al. 2022, Steidle et al. 2022). Collaborative projects such as the "BioDivKultur" project (Technische Universität Darmstadt 2022), which aims to improve the protection of arthropods on open green areas of cities, businesses, and agriculture, or the "InsectMow" project (Universität Hohenheim and Universität Tübingen 2022), in which insect- and spider-friendly disc mowers are being developed and evaluated, represent promising approaches to protect and strengthen biodiversity on grassland areas through an innovative form of management and improved mowing techniques.

References

BB-Umwelttechnik GmbH (2022): Warum ein Doppelmessermähwerk? https://doppelmessermähwerk.de/warum-ein-doppelmessermaehwerk/, accessed on 8 Apr 2022

Betz, O.; Kimmich, T.; Csader, M.; Spinner, F.; Steidle, J.L.M. (2022): Einsatz von Mähmaschinen mit schonender Wirkung auf die biologische Vielfalt zur Pflege von Straßenbegleitflächen am Beispiel des Grünpflegekopfs ECO 1200 plus® von MULAG. Biodiversity-preserving mowing machines for the maintenance of roadside areas – the example of the MULAG ECO 1200 plus® mowing head. Natur und Landschaft 97(9/10), S. 455–461

Blodgett, S.L.; Higgins, R.A.; Milliken, G.A. (1995): Blister Beetle (Coleoptera: Meloidae) Mortality Evaluated During Alfalfa Harvest. Journal of Economic Entomology 88(2), pp. 398–406, https://doi.org/10.1093/jee/88.2.398

Blüthgen, N.; Staab, M.; Achury, R.; Weisser, W.W. (2022): Unravelling insect declines: can space replace time? Biology Letters 18(4)

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2015): Indikatorenbericht 2014 zur nationalen Strategie zur biologischen Vielfalt, Berlin, 1. Aufl.

Claas Vertriebsgesellschaft mbH (2022): DISCO. Front-, Heck- und gezogene Mähwerke, Herzebrock

Claus, H.G. (1988): Halmfuttermähen und Halmfutterwerbung. Mäh- und Aufbereitungsmaschinen. In: Jahrbuch Agrartechnik, Band 1. Hg. Matthies, H.J.; Meier, F., Frankfurt/Main, Maschinenbau-Verlag, S. 87–89

Dernedde, W. (1969): Die Beschleunigung der Trocknung von Halmgut durch mechanische Aufbereitung. Dissertation, Georg-August-Universität Göttingen

Eichhorn, H. (1999): Ernte von Grünfutter, Silofutter und Heu. Mähwerke. In: Landtechnik. 136 Tabellen. Hg. Eichhorn, H., Stuttgart, Ulmer, 7. Aufl., S. 382–385

Fehr, A.; Fischer, R.; Fleischlin, S.; Friese-Tapmeyer, J.; Friske, R.; Ganzmann, H.; Gscheidle, R.; Gscheidle, T.; Heider, U.; Hohmann, B.; Huber, G.; van Huet, A.; Keil, W.; Lohuis, R.; Mann, J.; Petersen, M.; Schlögl, B.; Steidle, B.; Wimmer, A. (2016): Raufutterernte. In: Fachkunde Land- und Baumaschinentechnik. Hg. Fehr, A.; Fischer, R. et al., Haan-Gruiten, Verlag Europa-Lehrmittel Nourney Vollmer GmbH & Co. KG, S. 671–679

Fluri, P.; Frick, R.; Jaun, A. (2000): Bienenverluste beim Mähen mit Rotationsmähwerken. Schweizerisches Zentrum für Bienenforschung (Mitteilung Nr. 39)

Gardiner, T. (2006): The impact of Grassland Management on Orthoptera Populations in the UK. Dissertation, University of Essex

Gardiner, T.; Hassall, M. (2009): Does microclimate affect grasshopper populations after cutting of hay in improved grassland? Journal of Insect Conservation 13(1), pp. 97–102, https://doi.org/10.1007/s10841-007-9129-y

Fischer Maschinenbau GmbH & CO. KG (2020): EP2020081388W. Beutel, R.; Reber, D.

Hallmann, C.A.; Sorg, M.; Jongejans, E.; Siepel, H.; Hofland, N.; Schwan, H.; Stenmans, W.; Müller, A.; Sumser, H.; Hörren, T.; Goulson, D.; Kroon, H. de (2017): More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLOS ONE 12(10), e0185809, https://doi.org/10.1371/journal.pone.0185809

Hecker, L.P.; Wätzold, F.; Yang, X.; Birkhofer, K. (2022): Squeeze it or leave it? An ecological-economic assessment of the impact of mower conditioners on arthropod populations in grassland. Journal of Insect Conservation 26(3), pp. 463–475, https://doi.org/10.1007/s10841-022-00392-5

Hemmann, K.; Hopp, I.; Paulus, H. (1987): Zum Einfluss der Mahd durch Messerbalken, Mulcher und Saugmäher auf Insekten am Straßenrand. Natur und Landschaft 62(3), S. 103–106

Hensel, O. (2019): Futterernte: Langgutkette. In: Verfahrenstechnik in der Pflanzenproduktion. Hg. Köller, K.; Hensel, O., Stuttgart, Verlag Eugen Ulmer, S. 177–179

Hotz, S. (2013): Beim Mähen Leben retten - amphibien- und insektenfreundliches Mähwerk. Naturschutzinfo (1), S. 21

Humbert, J.-Y.; Ghazoul, J.; Richner, N.; Walter, T. (2010a): Hay harvesting causes high orthopteran mortality. Agriculture, Ecosystems & Environment 139(4), pp. 522–527, https://doi.org/10.1016/j.agee.2010.09.012

Humbert, J.-Y.; Ghazoul, J.; Sauter, G.J.; Walter, T. (2010b): Impact of different meadow mowing techniques on field invertebrates. Journal of Applied Entomology 134(7), pp. 592–599, https://doi.org/10.1111/j.1439-0418.2009.01503.x

Humbert, J.-Y.; Richner, N.; Sauter, J.; Walter, T. (2010c): Wiesen-Ernteprozesse und ihre Wirkung auf die Fauna, Ettenhausen

Humbert, J.-Y.; Ghazoul, J.; Walter, T. (2009): Meadow harvesting techniques and their impacts on field fauna. Agriculture, Ecosystems & Environment 130(1-2), pp. 1–8, https://doi.org/10.1016/j.agee.2008.11.014

Kemper, S.; Lang, T.; Frerichs, L. (2014): Der überlagerte Schnitt im Scheibenmähwerk - Ergebnisse aus Feldversuchen und Simulation. Landtechnik 69(4), S. 171–175, https://doi.org/10.15150/lt.2014.570

Kersten Maschinenfabrik (2022): Produktkatalog Landwirtschaft, D-46459 Rees

Kiel, E.-F. (1999): Heuschrecken und Mahd. Empfehlungen für das Pflegemanagement in Feuchtwiesengebieten. In: LOeBF-Mitteilungen, S. 63–66

Kraut, D. (1995): Schädigung der Kleintierfauna durch Mähwerke. Landtechnik 50(3), S. 138–139

MULAG Fahrzeugwerk Heinz Wössner GmbH & CO. KG (2020): EP 3 841 862 A2, Meißner, U.

Kremer, B.P. (2020): Die Wiese, Darmstadt, wbg Academic in Wissenschaftliche Buchgesellschaft (WBG), 2016. Aufl.

Kuhn Maschinen-Vertrieb GmbH (2021): RM Universalmulchgeräte - Produktinformation, D-39291 Schopsdorf-Genthin

Löbbert, M. (2001): Landschaftspflege. Bewertung technischer Verfahren unter besonderer Berücksichtigung der Wirbellosen-Fauna. Landtechnik 56 (SH1), S. 234–236, https://doi.org/10.15150/lt.2001.2149

Löbbert, M.; Kromer, K.-H.; Wieland, C.C. (1994): Einfluss von Mäh- und Mulchgeräten auf die bodennahe Fauna. In: Forschungsberichte „Integrative Extensivierungs- und Naturschutzstrategien“, S. 7–26

Maschinenfabrik Bernhard Krone GmbH & Co. KG (2022): EasyCut B. Mähkombinationen, D-48480 Spelle

Meiners, H.; Dietsche, S.; Lausen, G.; Rempfer, R. (2009a): Mähwerke. In: Land- und Baumaschinentechnik. Hg. Meiners, H., Hamburg, Handwerk und Technik, 17. Aufl., S. 395–401

Meiners, H.; Dietsche, S.; Lausen, G.; Rempfer, R. (2009b): Maschinen und Geräte zur Rasenpflege. In: Land- und Baumaschinentechnik. Hg. Meiners, H., Hamburg, Handwerk und Technik, 17. Aufl., S. 484–490

Meyer, J. (1998): Verfahren der Landschaftspflege. In: Landtechnik Bauwesen. Verfahrenstechniken - Arbeit - Gebäude - Umwelt. Hg. Schön, H., München, BLV-Verlagsgesellschaft, 9. Aufl., S. 399–405

Meyer, T. (2020): Schonende Flächenpflege liegt im Trend. Eilbote-Online 37

Oppermann, R.; Claßen, A. (1998): Naturverträgliche Mähtechnik. Moderne Mähgeräte im Vergleich. Naturschutzbund NABU Baden-Württemberg e.V.

Oppermann, R.; Johnen, S.; Bleil, R. (2012): Entwicklung eines faunaschonenden Mähgerätes - Begutachtung der Auswirkungen auf die Fauna. Institut für Agrarökologie und Biodiversität (IFAB), Mannheim, unveröffentlicht

Oppermann, R.; Krismann, A. (2001): Naturverträgliche Mähtechnik und Populationssicherung. Ergebnisse eines Workshops am 24.10.2000 im Bundesamt für Naturschutz (BfN) in Bonn und Kurzfassung der Ergebnisse der E & E Voruntersuchung, Bonn

Robinson, R.A.; Sutherland, W.J. (2002): Post-war changes in arable farming and biodiversity in Great Britain. Journal of Applied Ecology 39(1), pp. 157–176, https://doi.org/10.1046/j.1365-2664.2002.00695.x

Rux, S. (1999): Geräte und Verfahren zur Brachflächen- und Landschaftspflege. Mäh- und Mulchgeräte. In: Landtechnik. 136 Tabellen. Hg. Eichhorn, H., Stuttgart, Ulmer, 7. Aufl., S. 426–428

Saurma-Jeltsch, A.-K.; Münchhausen, S. von; Häring, A.M.; Kucznik, K.; Hübschmann, F.; Kitzmann, B. (2020): Mehrkosten der Nutzung eines Doppelmessermähwerks zur naturschutzgerechten Grünlandbewirtschaftung. Ergebnisse eines Praxisversuchs in Brandenburg

Schaefer, J. (1966): Möglichkeiten und Grenzen bei der Verwendung von hydraulischen Schwingantrieben für Mähwerke. Grundlagen der Agrartechnik 16(1), S. 30–34

Schön, H. (1998): Verfahrenstechnik der Futterernte, Futterkonservierung und Landschaftspflege. Mähverfahren. In: Landtechnik Bauwesen. Verfahrenstechniken - Arbeit - Gebäude - Umwelt. Hg. Schön, H., München, BLV-Verlagsgesellschaft, 9. Aufl., S. 334–340

Seibold, S.; Gossner, M.M.; Simons, N.K.; Blüthgen, N.; Müller, J.; Ambarlı, D.; Ammer, C.; Bauhus, J.; Fischer, M.; Habel, J.C.; Linsenmair, K.E.; Nauss, T.; Penone, C.; Prati, D.; Schall, P.; Schulze, E.-D.; Vogt, J.; Wöllauer, S.; Weisser, W.W. (2019): Arthropod decline in grasslands and forests is associated with landscape-level drivers. Nature 574(7780), pp. 671–674, https://doi.org/10.1038/s41586-019-1684-3

Steidle, J.L.M.; Kimmich, T.; Csader, M.; Betz, O. (2022): Negative impact of roadside mowing on arthropod fauna and its reduction with 'arthropod-friendly' mowing technique. Journal of Applied Entomology 146(5), pp. 465-472, https://doi.org/10.1111/jen.12976

Technische Universität Darmstadt (2022): BioDivKultur Homepage. https://biodivkultur.de/, accessed on 12 May 2022

Tscharntke, T.; Grass, I.; Wanger, T.C.; Westphal, C.; Batáry, P. (2021): Beyond organic farming - harnessing biodiversity-friendly landscapes. Trends in ecology & evolution 36(10), pp. 919–930, https://doi.org/10.1016/j.tree.2021.06.010

Tyler, G.A.; Green, R.E.; Casey, C. (1998): Survival and behaviour of Corncrake Crex crex chicks during the mowing of agricultural grassland. Bird Study 45(1), pp. 35–50, https://doi.org/10.1080/00063659809461076

Umweltbundesamt (2021): Indikator: Grünlandfläche. https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-gruenlandflaeche#die-wichtigsten-fakten, accessed on 1 Apr 2022

Universität Hohenheim; Universität Tübingen (2022): InsectMow Homepage. https://insectmow.uni-hohenheim.de/, accessed on 12 May 2022

van de Poel, D.; Zehm, A. (2014): Die Wirkung des Mähens auf die Fauna der Wiesen - Eine Literaturauswertung für den Naturschutz. Anliegen Natur 36(2), S. 36–51

Vickery, J.A.; Tallowin, J.R.; Feber, R.E.; Asteraki, E.J.; Atkinson, P.W.; Fuller, R.J.; Brown, V.K. (2001): The management of lowland neutral grasslands in Britain: effects of agricultural practices on birds and their food resources. Journal of Applied Ecology 38(3), pp. 647–664, https://doi.org/10.1046/j.1365-2664.2001.00626.x

Wagner, C. (2004): Passive dispersal of Metrioptera bicolor (Phillipi 1830) (Orthopteroidea: Ensifera: Tettigoniidae) by transfer of hay. Journal of Insect Conservation 8(4), pp. 287–296, https://doi.org/10.1007/s10841-004-0404-x

Wilke, N. (1992): Beeinflussung von Heuschrecken durch Mahd und verschiedene Mahdsysteme in wechselfeuchten Wiesen norddeutscher Flussauen. Diplomarbeit, Technische Universität Braunschweig

Willner, W. (2013): Taschenlexikon der Käfer Mitteleuropas. Die wichtigsten Arten im Porträt. Wiebelsheim, Quelle & Meyer

Zieger, S. (2021): Technische Umsetzung insektenschonender Pflege von Weg- und Straßenrändern - Produktübersicht. Landschaftspflegeverband Göttingen e.V.

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