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RESEARCH ARTICLE

Riparian reforestation on the landscape scale: Navigating trade-offs among agricultural production, ecosystem functioning and biodiversity

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Abstract

1. Stream–riparian networks are subject to multiple human pressures that threaten key functions of aquatic and terrestrial ecosystems, drive habitat and diversity losses, affect riparian connectivity and cause stakeholder conflicts. Designing riparian landscapes in a way that they can simultaneously meet multiple competing demands requires a clear understanding of existing trade-offs, and a landscape-scale perspective on the planning of reforestation measures.
2. This study applied a landscape optimization algorithm for allocating riparian forest management measures in the intensively used agricultural catchment of the Zwalm River (Belgium). We optimized forest allocation to improve stream ecological quality (EPT index), functional diversity (diatoms) and riparian carbon processing (cotton-strip assay), while minimizing losses in agricultural production potential. Regression models were developed to predict the target indicators for 489 segments of the Zwalm riparian corridor, using spatial variables on three different scales. For each riparian segment, we developed spatially explicit management measures, representing different intensities of riparian reforestation. The allocation and combination of these measures in the riparian corridor were optimized to identify (a) trade-offs among the target indicators, (b) priority regions for reforestation actions and (c) the required reforestation intensity.
3. The results showed that all target indicators were affected by the area share of riparian forests and its landscape-scale configuration. Reforestation of the Zwalm riparian corridor could significantly improve indicators for biodiversity and ecosystem functioning (e.g. up to +96% for EPT index), but would lead to a strong trade-off with agricultural production. By optimizing the placement of management measures, we showed how these trade-offs could be best balanced.

4. The headwater regions of the Zwalm were identified as priority regions for reforestation actions. Facilitating connectivity among and further expansion of existing forest patches in the Zwalm headwaters showed to improve ecosystems with minimized trade-offs.
5. *Synthesis and applications*. This study demonstrates, for the first time, the potential of landscape optimization algorithms to support the management and design of multifunctional stream–riparian networks. We identified riparian reforestation solutions that minimized trade-offs between specific natural values and societal needs. Our spatially explicit approach allows for an integration into spatial planning and can inform policy design and implementation.

KEYWORDS
biodiversity, ecosystem functioning, ecosystem services, forest riparian buffers, multi-objective optimization, riparian management, spatial planning, trade-off

1 | INTRODUCTION

Riparian habitats bordering streams and rivers are critical landscape features that provide a variety of ecosystem services and fundamental functions at the terrestrial–aquatic interface (Gundersen et al., 2010; Kuglerová et al., 2014; Naiman & Décamps, 1997). Their ecological importance comes along with a high socio-economic value (Colby & Wishart, 2002; Findlay & Taylor, 2006; Vollmer et al., 2015), which results in widely discussed conflicts regarding the management of riparian zones (Cole et al., 2020; Singh et al., 2021). These conflicts are exacerbated by the limited spatial extent of riparian areas, as these important habitats account for only a small proportion of land cover, for example, about 2% of the European continental area (Clerici et al., 2011, 2013).

Agricultural land-use, industries and human settlements have long encroached into riparian areas, making riparian habitats generally and riparian forests, in particular, some of the most degraded ecosystems worldwide (Décamps et al., 1988; Nilsson & Berggren, 2000). Currently, there is an increasing emphasis placed on the need to manage agricultural catchments as multifunctional landscapes, capable of supporting agricultural production, biodiversity and key ecosystem services (Fischer et al., 2017; O'Farrell & Anderson, 2010). Within this context, restoration of riparian areas in agricultural catchments might be beneficial for multiple objectives. Riparian forests provide habitats and corridors for the movement of biota (de la Fuente et al., 2018; Naiman & Décamps, 1997), regulate stream water temperature via shading (Beschta, 1997; Studinski et al., 2012), control the runoff of sediments and nutrients (Barling & Moore, 1994) and increase soil carbon stocks (Dybala et al., 2019). Moreover, riparian forests are widely recognized for their social and recreational values (Rodewald & Bakermans, 2006). However, as reforestation and other shifts in land-use involve unavoidable trade-offs, it is important to understand the conflicts between competing objectives and to find feasible solutions mitigating them.

Previous studies prioritized the placement of riparian forest buffers based on landscape analysis techniques (Tomer et al., 2009) or compared a limited number of catchment-scale strategies for the placement of riparian forests regarding their cost-effectiveness (Qiu & Dosskey, 2012). Target indicators of those approaches were frequently related to the improvement of chemical water quality or erosion control and rarely addressed biodiversity goals, as their projection is often accompanied by a high degree of uncertainty—particularly on larger scales. Nevertheless, Sickle et al. (2004) successfully developed predictive models for estimating the status of fish and aquatic invertebrate communities across a whole stream network using parameters related to the land-use and physiography of the riparian corridor. Furthermore, Bentrup and Kellerman (2004) presented a geographical information system (GIS)-based filter method to identify critical gaps in the connectivity of riparian forests based on the dispersal capabilities of selected species.

Optimization algorithms have the potential to further enhance the large-scale management of riparian buffers as they allow for an integrated perspective on competing objectives within one spatial framework. Such algorithms have been successfully applied for the identification and quantification of trade-offs as well as in the context of landscape planning and management within agricultural, urban and forest landscapes (Baskent & Keles, 2005; Kaim et al., 2018; Memmah et al., 2015; Schwarz et al., 2020). Using spatially explicit management options within the optimization, spatial priorities for the allocation of measures or specific Pareto-optimal maps can be identified that provide landscape planners with alternative solutions for balancing existing trade-offs (Verhagen et al., 2018).

However, up to now no optimization study specifically addressed the restoration of riparian areas. Some of the reasons for that might be the lack of data (spatial and empirical) and suitable models as well as the linear character and limited geographical scope of riparian areas that pose particular challenges to the design of an optimization framework.

This paper presents the first spatially explicit multi-objective optimization of a stream–riparian network considering riparian reforestation as the main management measure. We consider different intensity levels of reforestation and land-use-specific constraints. Indicators for biodiversity, ecosystem functioning and agricultural production are used to evaluate forest allocation during the optimization procedure. The corresponding statistical models to predict those indicators in response to riparian management have been developed specifically for our study catchment (Zwalm River) using monitoring data acquired as part of the European BiodivERsA 'CROSSLINK' project (Burdon et al., 2020) as well as data derived from a comprehensive GIS-based spatial analysis. We analysed our outcomes for trade-offs between the target indicators and identified spatial priorities for riparian forest management measures in an intensively used agricultural catchment.

2 | MATERIALS AND METHODS

2.1 | Study area and data collection

The Zwalm River is located in Flanders and is part of the Belgian loess belt—an undulating landscape that historically was a tree-dominated ecosystem, but is impacted by humans since thousands of years. First farmers arrived about 7,300 years ago (Langohr, 2019) and nowadays this region is dominated by intensive agriculture. Hydrographically, the river belongs to the Upper Scheldt and drains 117 km^2 over a stream length of 22 km with a mean annual flow of 1.21 m^3/s (Carchon & De Pauw, 1997). While the headwater streams are partly forested, some downstream parts are severely degraded, with moderate to very poor habitat quality (Dedecker et al., 2004). Agricultural land (arable land and different types of managed grassland; in total 74% of the area) is by far the dominant land-use of the catchment (Figure 1), soils are prone to erosion and significant agricultural runoff is generated. Moreover, urban wastewater as well as structural and morphological

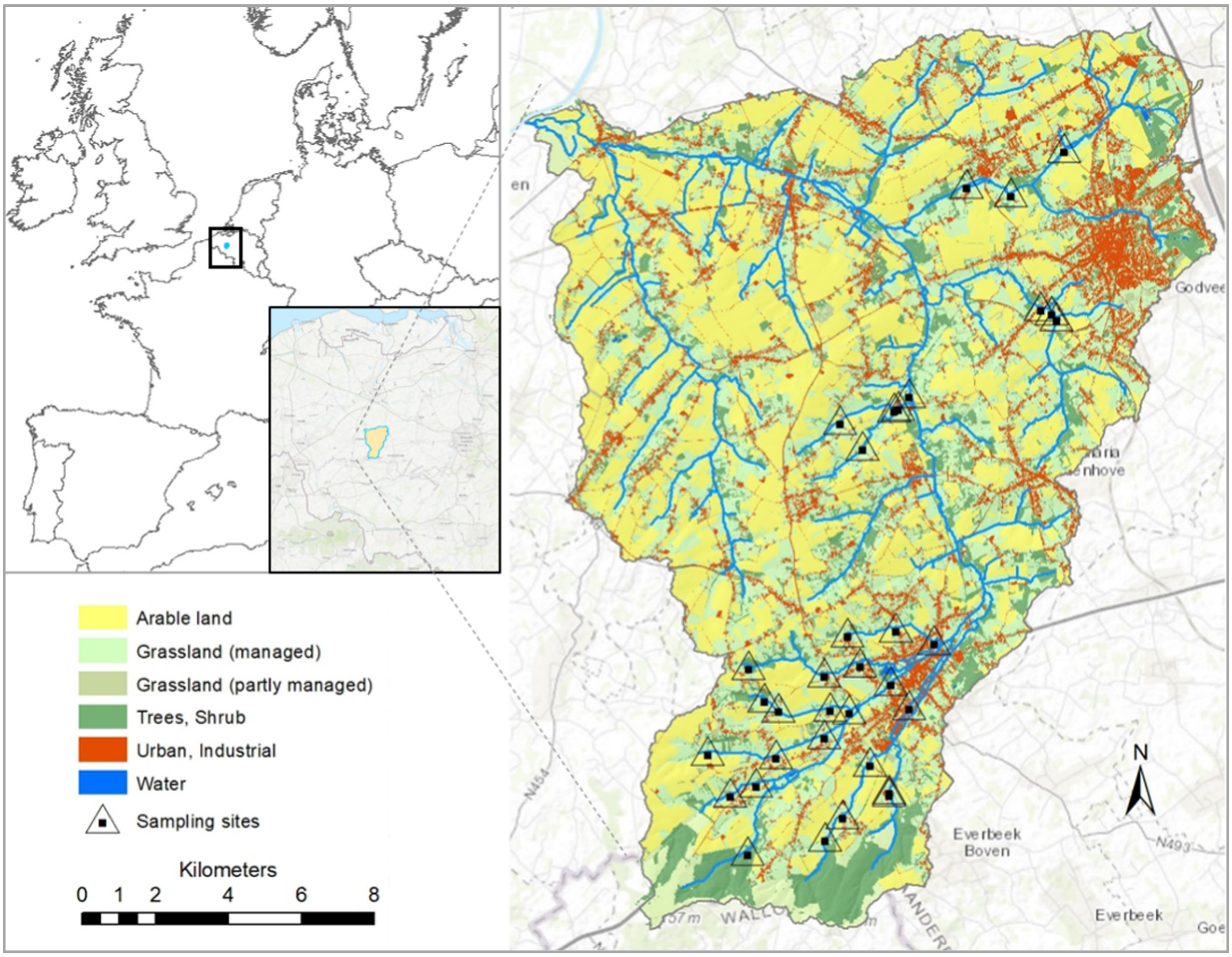

FIGURE 1 Land-use in the Zwalm catchment in Flanders (Belgium), including the sampling sites of the CROSSLINK measurement campaign. Arable land is conventionally managed in large parts, with winter wheat, potato, winter barley and silage maize being the most important crops

disturbances (e.g. weirs, artificial embankments) negatively affect the overall condition of the river and its tributaries. However, some headwaters of the Zwalm are less polluted and colonized by rare fish species and several vulnerable macroinvertebrates (Boets et al., 2021; Dedecker et al., 2004; Soresma, 2000).

Agricultural land-use also heavily encroaches into the riparian areas of the Zwalm catchment, accounting for 64% of riparian area. Large parts of that are different types of managed grassland (49%), which are used for grazing and hay production. Apart from the headwaters, patches of riparian tree cover are rather small and often limited to a single line of trees along the stream. In total, trees cover 26% of the riparian area.

The Zwalm River has been selected as a case study in the BiodivERsA project CROSSLINK, which investigated the role of forested riparian buffers in modified European landscapes by measuring a wide range of ecosystem attributes in stream–riparian networks (Burdon et al., 2020; Forio et al., 2020, 2021). To investigate the cumulative impacts of riparian land-use, the CROSSLINK project executed a highly standardized field sampling campaign (see Supporting Information S1–S3) at different types of sampling sites: five least disturbed headwater sites, nine independent stream-site pairs, each consisting of a stream reach with a forested riparian buffer paired with an unbuffered section upstream, as well as 11 downstream sites. The measured variables quantified attributes of habitat condition, biodiversity and ecosystem functioning in aquatic and terrestrial habitats. The dataset was used for selecting the environmental target indicators and developing the corresponding statistical models of this study. Our study did not require ethical approval or permission for fieldwork.

2.2 | Target indicators

To address multiple attributes of biodiversity and ecosystem functioning, we selected three environmental objectives, namely stream ecological quality, functional diversity (diatoms) and riparian carbon processing. Indicators for stream–riparian conditions of the Zwalm River were used to represent those objectives (see sections below). The required samples were collected in the years 2017 (diatoms, cotton-strips, macroinvertebrates) and 2018 (macroinvertebrates) from 34 sampling sites as part of the CROSSLINK measurement campaign (Burdon et al., 2020; Forio et al., 2020). As the implementation of environmental measures, such as reforestation of agricultural land, comes at the cost of agricultural production, a fourth indicator was selected, conceptually representing the amount and productivity of agricultural land which will be lost.

2.2.1 | Stream ecological quality (EPT index)

To represent the ecological quality of the streams, the 'EPT' macroinvertebrate taxa richness indicator was selected. The EPT index is a standard index used in the assessment of the ecological status of freshwater systems, and is calculated based on the combined taxa richness of three macroinvertebrate orders which have a generally low tolerance to environmental degradation associated with, for example, water pollution, elevated fine sediments and low oxygen: Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) (Barbour et al., 1999). Higher values of the EPT index thus indicate a higher ecological status (Weber, 1973).

2.2.2 | Functional diversity (diatoms)

Our second metric was an index of the functional diversity of benthic diatoms, a key component of benthic algal biofilms. Algal biofilms mediate key ecosystem processes in stream ecosystems, including rates of nutrient uptake, and ecosystem production, with diatoms in particular serving as a high-quality food resources for invertebrate and vertebrate consumers. Functional diversity metrics are calculated based on species traits, that is, phenotypic characteristics of species that regulate their responses to environmental variation and effects on ecosystem functioning (Violle et al., 2007). Communities with a greater diversity (both richness and evenness) of functional traits are often associated with more efficient ecosystem functioning (Cardinale, 2011; Frainer et al., 2014). Recent studies found strong relationships between traits and habitat properties (Frainer & McKie, 2015; Schneider et al., 2017), suggesting that functional diversity can be linked to ecosystem stability. In our study, we scored diatoms for their species traits based on classifications given in the freshwaterecology.info database, and used these scores to calculate diatom functional evenness.

2.2.3 | Riparian carbon processing and permanence

Organic-matter decomposition is a fundamental ecosystem process that contributes to global carbon cycling by regulating local carbon stocks and fluxes (Battin et al., 2009). Biological activity drives carbon processing, which can be stimulated by excess nutrients leading to rapid carbon losses (Rosemond et al., 2015). We used data on the breakdown of cotton-strips in riparian soils as a standardized method to measure organic-matter decomposition and provide information on the capacity of riparian ecosystems to retain organic carbon (Tiegs et al., 2013, 2019). We deployed four cotton-strips in two blocks to each riparian sampling site for 36 days. The decomposition of cellulose reduced the maximum tensile strength (Newtons) of the incubated cotton-strips. High tensile strength of incubated cotton-strips indicates less decomposition, higher turnover time and benefits for carbon storage (Tiegs et al., 2019). In the context of a nutrient-enriched landscape, we regard a higher final tensile strength as indicative of improved riparian carbon processing overall, since this indicates a buffering of the potentially stimulating effects of nutrients on the microbially mediated decomposition of cotton-strips. Fast decomposition is more likely to result in the leaching of mineralized carbon from soil surface layers. Slow decomposition rates result in the building up of soil organic matter stocks, increase the time available for transfer of carbon into biomass of larger, longer-lived organisms and well as for bioturbation of carbon into deeper soil layers (Krishna & Mohan, 2017; Prescott & Vesterdal, 2021). Thus, we used the remaining tensile strength as an indicator of the processing and permanence of carbon in riparian soils. Further information on our cotton-strip assay is available in S1 (Supporting information).

2.2.4 | Agricultural production potential

A fourth target indicator has been considered to represent the provisioning service of agricultural production that might be lost as a result of the conversion of agricultural land into riparian forest. We rather conceptually defined this 'agricultural production potential' as a function of the agricultural area (arable land and pasture) and its related average soil fertility. Soil fertility was approximated using a dataset of the Flanders Regional Ecosystem Assessment on the biophysical suitability for food production (Stevens et al., 2015; Van Gossum et al., 2014). The 'agricultural production potential' was calculated based on a look-up table approach where the agricultural area (m^2) of a riparian segment (see Section 2.3.1) is weighted by its average biophysical suitability for food production. A decreasing amount of agricultural area due to reforestation will lead to a decline of the 'agricultural production potential' of a riparian segment, thus indicating potential trade-offs between the objectives.

2.3 | Spatial set-up and model development

2.3.1 | Riparian corridors, stream segments and catchments

The spatial representation of the Zwalm stream–riparian system within our modelling and optimization framework was based on segments with a length of 300 m along the river course. In total, 489 stream segments were defined using data from the hydrographic atlas of Flanders (VMM, 2018) and an ArcGIS toolbox of Broad (2017). In the next step, we defined regions that potentially affect the status of an individual river segment. For each of the 489 stream segments, we thus derived three spatial reference units (Figure 2): (a) its local riparian corridor, represented by a curved 300 m × 100 m polygon along the stream channel; (b) its full riparian corridor within in the upstream catchment; and (c) its total upstream catchment area. For both types of riparian corridors (local and total) a fixed width of 100 m (50 m on each side of the stream) was defined, which is in accordance with other studies considering local riparian properties (esp. land-use) in model-based ecological studies (Damanik-Ambarita et al., 2018). The spatial reference units defined the spatial set-up of our modelling approach. For each riparian segment, a pool of reforestation scenarios (having different dimensions of forest buffers) was developed (see Section 2.4.1). More information on the delineation of the spatial reference units is given in S4.

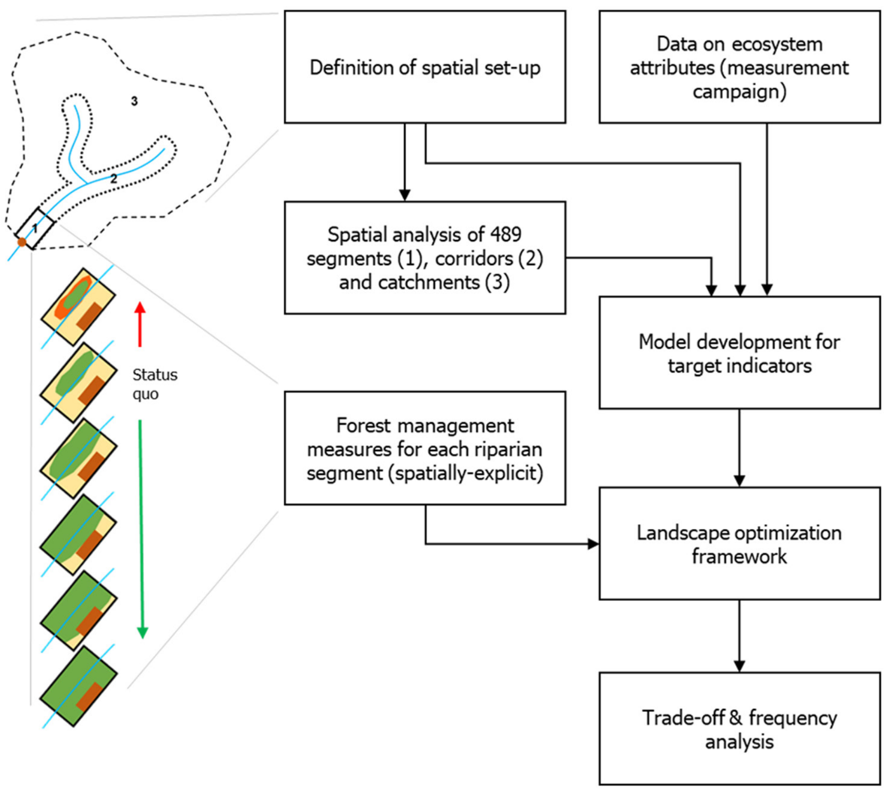

FIGURE 2 Workflow for the spatially explicit multi-objective optimization of the Zwalm riparian corridor

2.3.2 | Spatial analysis and explanatory variables

We developed four sets of explanatory variables that served as the starting point of model development. In the following, we describe the main characteristics (details are given in S5–S7). Potential candidates of model variables have been restricted to those that could be derived for a catchment-wide coverage, ensuring the availability of predictor data for each of the 489 riparian segments. All predictor variables have been derived using ArcPy scripting and R (R Core Team, 2019).

The first set of variables addressed the land-use properties of each spatial reference unit of each riparian segment. A 1 m resolution land-cover dataset (Agentschap Informatie Vlaanderen, 2016) was used to derive the areal percentages for each land-use category. Additionally, we derived the average, maximum and minimum width of each land-use in each local segment.

The second set of variables quantified the average distance between patches of riparian forest in the riparian corridor upstream a river segment. Spatial resilience theory posits that greater ecological connectivity, that is, in the movements of organisms and material among habitat patches in a larger habitat network, will enhance overall resilience across the habitat network (Peterson et al., 1998; Truchy et al., 2015). We used the distance between forest patches as a proxy for their potential connectivity. A prerequisite for these calculations was the definition of a minimum size of a forest patch to be relevant. Three different patch sizes have been tested using grid cells with an edge length of 25, 50 and 100 m.

Physiographic characteristics were used as a third set of explanatory variables. We derived data for catchment size, steepness and elevation (average, maximum and minimum) for all spatial reference units of each riparian segment. Additionally, we differentiated the agricultural crop yield potential between regions using data of the Flanders Regional Ecosystem Assessment (Stevens et al., 2015; Van Gossum et al., 2014).

The fourth set of variables was established to consider the network position of a segment in the whole riparian catchment. Network position was addressed using interaction terms of two variables combining local and upstream properties. The hypothesis behind these interaction terms was that an effect of a local land-use attribute (e.g. local share of riparian forest) is dependent on the amount of upstream stressors (e.g. agricultural area upstream) or on more general variables such as the catchment size upstream.

2.3.3 | Model development

Assessing the effects of riparian reforestation within an optimization environment requires the development and linkage of predictive models for each target indicator. While the calculation of the 'agricultural production potential' was based on a look-up table approach (see section 2.2.4), for each of the three 'environmental' target indicators a simple and robust regression model was developed. Data on the explanatory variables described above were used to predict the monitoring data of the response variables (i.e. EPT index, diatom functional evenness, cotton-strips tensile strength). The position of the sampling sites corresponds to the starting point of a river segment. Thus, 34 of the 489 Zwalm riparian segments were used for model development.

The large number of predictor variables, their potential multicollinearity and the relatively small number of data points for the response variables (34 sampling sites) required a careful selection of predictor variables. Therefore, a two-step model development process was applied consisting of a supervised preselection of explanatory variables and a model simplification procedure. Details on both procedures and data preparation are given in S8.

Between four and nine 'best' explanatory variables were preselected for each response variable and served as starting point of an automated model simplification for multiple linear regression models. We applied the function 'ols_step_all_possible' of the R package OLSRR (Maechler et al., 2019), which tests all possible subsets of the set of potential independent variables. For model comparison, we used the Akaike information criterion (Akaike, 1974), adjusted R^2 and predictive R^2. By summing up their ordered ranks across all tested models, all three evaluation criteria were combined for selecting the best model. To cross-validate the final composition of models and to investigate the effects of a potential spatial autocorrelation of the sampling sites, we carried out an independent manual model simplification procedure using linear mixed-effects models (S8). This alternative model simplification approach confirmed the suitability of the selected predictors. The final models have been programmed into Python scripts to calculate the four target indicators for each of the 489 riparian segments within the optimization framework.

2.4 | Optimization approach

2.4.1 | Explorative forest management measures

As the theoretically possible number of options to increase and allocate riparian forest is extremely high, we developed a set of explorative forest management measures. These measures are spatially explicit and represent different intensities of riparian reforestation within each riparian segment. The total area available for reforestation was determined considering land-use-specific constraints, thus excluding urban and water areas. Starting at the status quo (QUO), the explorative management measures gradually increased the share of riparian forest in five steps (Figure 2), by always converting additional 20% of the available area into forest (ReFor20%, ReFor40%, ReFor60%, ReFor80%, ReFor100%). Furthermore, one measure was considered that decreased existing forest patches by 20% of their initial area (DeFor20%) and converted these areas into agricultural land. Thus, potential benefits beyond the current legal framework (protecting existing forests) could be investigated. As defined by our spatial modelling units, the maximum buffer width we could address was 100 m (ReFor100%).

The explorative forest management measures were prepared separately for each riparian segment and all measures were translated into an individual map, which resulted in 3423 segment-based maps in total (see S9, e.g. of map translation). This approach allowed for a flexible recombination of segment-scale measures to new catchment-scale solutions within the optimization framework. For the map translation of our measures, we assumed that already existing forest patches of a riparian segment would be evenly increased. If there was no forest in a segment at the status quo, an initial forest patch along the river course was generated. Land-use constraints were considered directly during map generation.

2.4.2 | Landscape optimization algorithm

We used a multi-objective genetic algorithm to optimize the combination and allocation of forest management measures in the riparian corridor of the Zwalm River. All four target indicators were simultaneously used as objective functions. Within the Python environment of the landscape optimization tool CoMOLA (*Constrained Multi-objective Optimization of Land-use Allocation*, Strauch et al., 2019), we linked all models, including their spatial set-up, to the non-dominated sorting genetic algorithm II (NSGA-II, Deb et al., 2002).

Genetic algorithms code the parameters to be optimized in a genome, which is carried by an individual. Within our study, the genome was a string of 489 integers, each representing one riparian segment and its corresponding forest management measure. Accordingly, the full riparian corridor of one catchment-scale solution was an individual carrying that genome. The decision space of our set-up covered seven management measures for each of the 489 riparian segments, which resulted in a gene pool of 3423 (7*489) and in 7^{489} possible catchment-scale combinations.

Within an evolutionary process that involves selection (based on the modelled fitness values) and variation (i.e. crossover and mutation of genomes) of individuals over a number of generations, CoMOLA approaches towards the global optimum of measure combinations in the riparian corridor. A detailed description of this evolutionary process is given in S10. For each generation of individuals, a Pareto-ranking was applied on their modelled fitness values and individuals with the best Pareto-rank form a Pareto-front. For each individual on that front, the value of any one target indicator cannot be improved without losing some quantity of at least one other target indicator. The Pareto-front thus represents the so far identified optimal (minimal) trade-off between all target indicators considered in the analysis.

No optimization algorithm can guarantee identification of the global optimum due to the vast number of possible solutions and the finite number of generations that can be tested. Nevertheless, genetic algorithms are known to find at least close to optimum solutions in a reasonable run-time (Deb et al., 2002; Lautenbach et al., 2013). To limit the computation time of our experiment to a reasonable extent, we ran CoMOLA with a population size of 250 individuals, using a predefined number of generations (400) as termination criteria. We thus generated and evaluated a total of 100,250 combinations of forest management measures in the Zwalm riparian corridor. The crossover and mutation rate were set to values of 0.9 and 0.1, respectively, and the initial population included boundary solutions (seeds) for each measure as recommended by Strauch et al. (2019).

2.4.3 | Evaluation and frequency analysis

To evaluate the performance of the optimization and the suitability of the termination criteria, we calculated the hypervolume of the Pareto-fronts (Zitzler & Thiele, 1999) using the R package MCO (Mersmann, 2014). The hypervolume metric is measuring the convergence and diversity of the non-dominated solutions space of each generation and can indicate if the solutions get closer to the true Pareto-front and are evenly scattered (Jiang et al., 2014).

Multi-objective optimization typically results in numerous optimal solutions that are difficult to translate into targeted spatial planning advices (Karakostas, 2017). To identify priority areas of specific forest management measures, we followed the approach of Verhagen et al. (2018) and calculated the relative frequency each measure was assigned to a riparian segment across the whole Pareto-optimal solutions space. This approach identified the dominant measure of each riparian segment and points out segments where a specific measure was (almost) always selected irrespective of its location at the Pareto-front.

3 | RESULTS

3.1 | Case study specific models and sensitive variables

The results of the model development showed that a variety of land-use and physiographic characteristics (11 spatial predictors) on all three scales (local, riparian and catchment) affected the status of the four target indicators (Table 1). The most relevant spatial unit and variable of the final models was the local segment and its forest cover, respectively. Increasing forest shares (forest land-use [%] of riparian segments) led to benefits for all 'environmental' target indicators (stream ecological quality, functional diversity, riparian carbon processing and permanence). However, the magnitude of improvement was partly dependent on network position aspects (represented by interaction terms), specifically by properties of the upstream riparian corridor (e.g. distance between forest blocks) and catchment (e.g. size of the upstream catchment). Other types of land-use (arable, urban and pasture), as well as an increasing distance between riparian forest patches, showed negative effects on individual target indicators.

The final models included between three and five explanatory variables and are summarized in Table 1 (see S11 for details). Model evaluations showed coefficients of determination (R^2) of 0.37–0.61, adjusted R^2 of 0.3–0.54 and p-values of <0.001–0.008. Variance inflation factors were less than 2.0 for all coefficients on model terms, except for interaction terms and their components. The extreme

TABLE 1 Overview on the predictor variables of the final models developed for the Zwalm River. Arrows indicate the effect of a variable on the model results. Stars indicate an interaction term

		Stream ecological quality (EPT index)	Riparian carbon processing and permanence	Functional diversity (diatoms)	Agricultural production potential
Evaluation of full model (R^2, adj. R^2, p-value)		0.61/0.54/<0.001	0.42/0.36/0.002	0.37/0.3/0.008	–/–/–(conceptual)
Land-use variables	*Land-use of local riparian segment*				
	Forest & shrub [%]	↑*1,2	↑	↑*4,5	
	Pasture & grassland [%]		↓		↑
	Arable land [%]		↓*3		↑
	Land-use of full riparian corridor upstream				
	Forest & shrub [%]	↑*1			
	Distance btw. Riparian 100 m forest blocks [m]		↓*3	↓*5	
	Land-use of catchment upstream				
	Urban-Industrial [%]	↓			
Physiographic variables	*Properties of local riparian segment*				
	Elevation (mean) [m]			↓	
	Elevation (gradient) [m]	↑			
	Biophysical suitability food production [%]				↑
	Properties of catchment upstream				
	Catchment size [m]			↑*4	
	Elevation (gradient) [m]	↑*2			

*1,2,3,4,5 Stars indicate an interaction term. Numbers behind stars indicate which variables form an interaction term (e.g. *1 × *1, *2 × *2).

forest management measures DeFor20% (20% deforestation) and ReFor100% (100% reforestation) have been used to check the plausibility of the final models within all 489 riparian segments (without spatial optimization). When comparing both settings, an increase in stream ecological quality (EPT index: 1.9 vs. 4.2), slowed riparian carbon processing (maximum tensile strength: 201 vs. 338 Newtons) and functional diversity (diatoms: 0.48 vs. 0.49), as well as a decrease in agricultural production potential (6.2 Mio vs. 294), were observed.

3.2 | Pareto-optimal composition and trade-offs between targets

The optimization of the Zwalm riparian corridor resulted in 4001 Pareto-optimal solutions, each with a different combination and allocation of forest management measures as well as fitness values of the target indicators. The hypervolume evolution converged laterally towards a threshold, which indicates that our results might be a good approximation of the optimal solution space (S12). We visualized the trade-offs between the target indicators as a four-dimensional plot of all optimal solutions identified (Figure 3; Figure S13). Stream ecological quality and functional diversity (diatoms) both benefited from the expansion of riparian forests, as did soil carbon processing, which generally slowed as riparian forest increased. However, the dimension of improvement varies widely between those target indicators. Benefits were particularly high for stream ecological quality (up to +96.0%) and carbon processing (slowed by up to +51.1%), while the effects on functional diversity were rather minor (up to +5.2%).

Increasing riparian forests shares mainly came at the cost of agricultural production potential, which led to a considerable trade-off especially with stream ecological quality and riparian carbon processing. However, a slight increase in ecological quality (up to +3.8%), functional diversity (up to +1.8%) and slowed carbon processing (by up to +3.1%) could also be achieved without losses in agricultural production potential. These gains could be achieved by rather minor re-placements of riparian forests in the catchment from fertile areas to less fertile areas, but improved forest connectivity.

Only minor trade-offs have been observed among the three environmental target indicators themselves. Stream ecological quality showed the most significant response to changes in riparian forest cover, but the overall trend was comparable with riparian carbon processing. The response of our functional diversity metric was partly contrasting and showed somewhat different preferences regarding the optimal allocation of riparian forests.

3.3 | Intensity and spatial priorities for forest management measures

The analysis of the relative frequency of each measure within all Pareto-optimal solutions showed that intensive reforestation (ReFor100%; frequency: 31.4%) and slight deforestation (DeFor20%;

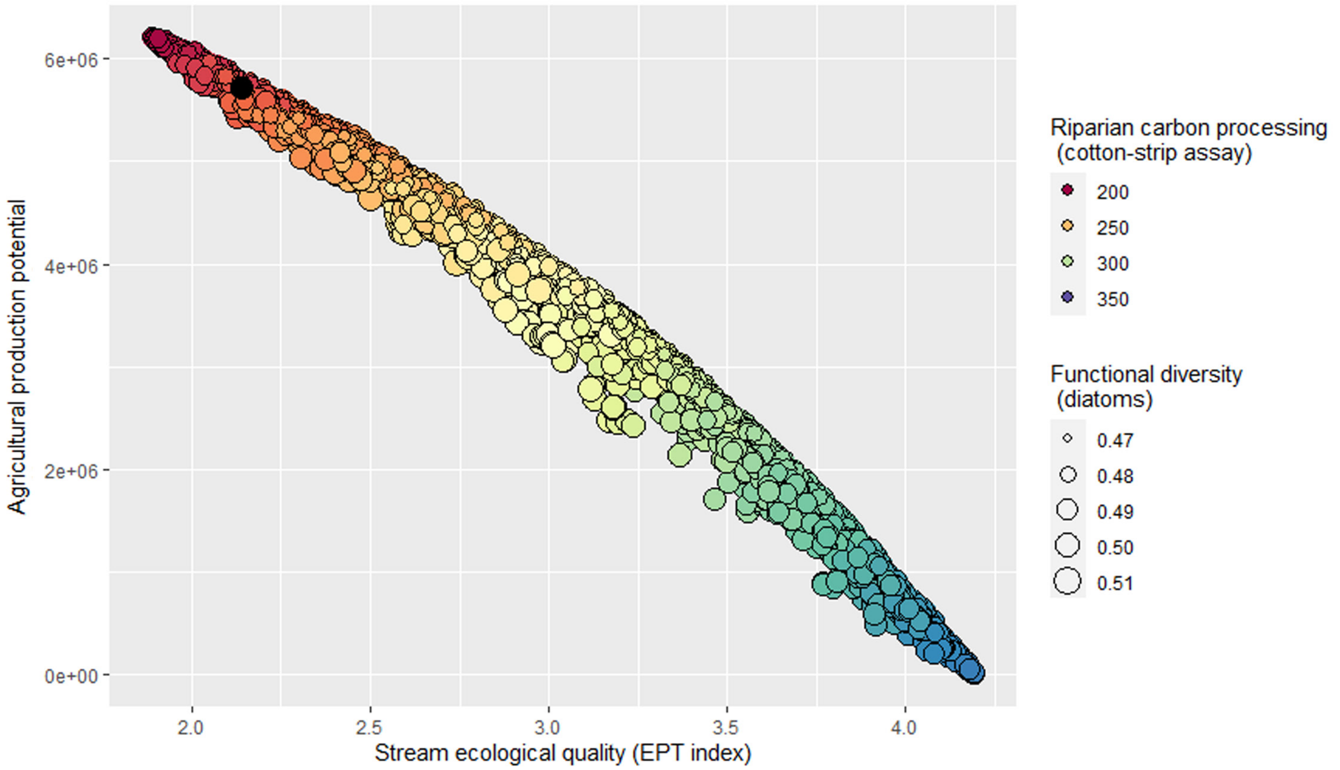

FIGURE 3 Visualization of the four-dimensional Pareto-front of all optimal solutions identified with CoMOLA. Each point represents a single catchment scale combination of 489 segment-scale forest management measures. The black dot represents the status quo. The four-dimensional plot can be used to quantify trade-offs between the target indicators

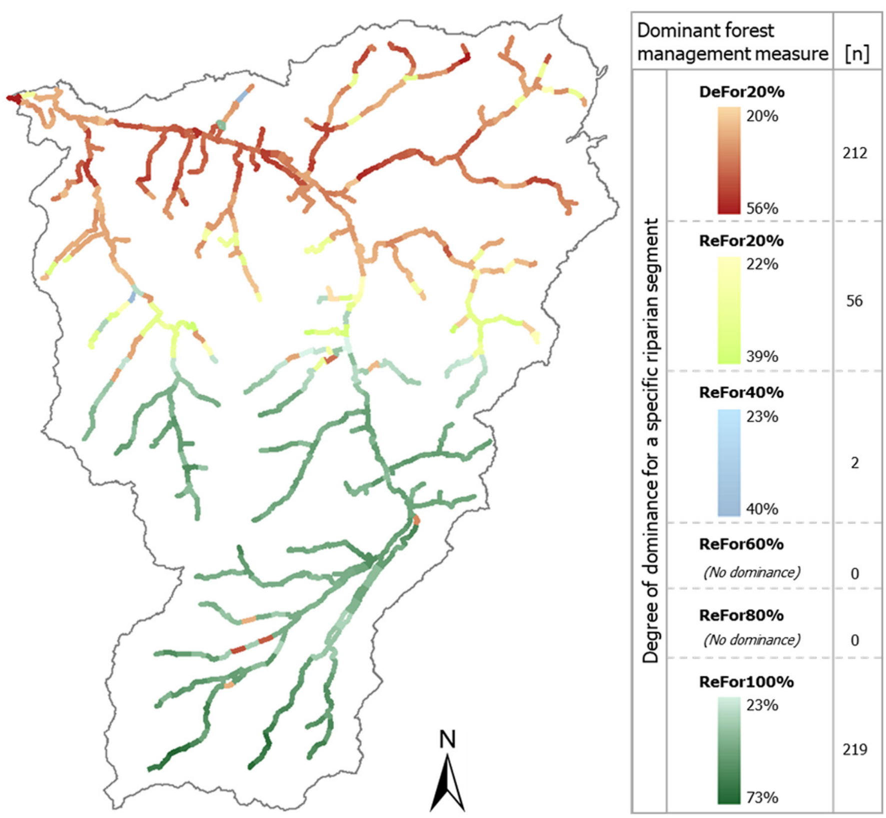

FIGURE 4 Spatial priorities for forest management measures in the riparian areas of the Zwalm River across all Pareto-optimal solutions. For every riparian segment, the most dominant management option is shown by its base colour (red, yellow-green, blue, green). The base colours are further differentiated by a gradient (colour ramp), indicating the degree of dominance [%] within a specific riparian segment. [*n*] is the number of segments where a measure is dominant. The four target indicators (model results) of this specific scenario are given in S14

frequency: 29.1%) were the most relevant options to adapt forest management in the riparian corridor. A slight increase in existing forest patches (ReFor20%; frequency: 16.2%) was the third most relevant option, while all other measures (ReFor40%, ReFor%60 and ReFor80%) only had frequencies between 4% and 7%. On average across all Pareto-optimal solutions riparian forest increased from 26% to 55%, which led to average benefits of 45% for stream ecological quality and 25% for riparian carbon permanence.

High variability was observed with respect to the degree to which a management measure showed to be the dominant solution for an individual riparian segment. In riparian segments where ReFor100% was the dominant solution, also its average degree of dominance was often very high (46.7%). Segments where DeFor20% (avg. dominance: 37.0%) and ReFor20% (avg. dominance: 31.4%) have been the dominant solutions showed much more variability in their allocated measures.

The three most relevant management measures also showed clear spatial priorities for their positioning in the catchment. While ReFor100% was especially relevant in the southern parts of the catchment, DeFor20% was most often chosen in the northern and more downstream regions. ReFor20% was especially allocated in the central part of the catchment as a kind of transition zone between the two extreme options (Figure 4).

When considering the average forest distribution across all Pareto-optimal solutions and the absolute change in forest shares (Figure 5), it can be observed that within the optimization experiment the existing forest patches of the upstream headwaters were connected with each other and expanded further downstream, thus largely increasing the existing headwater forests. This headwater forest extension was suspended at some locations in the centre of the municipality Brakel. Here, the increase in riparian forests is constrained by urbanized areas and thus the final average forest share in this area is rather low, although ReFor100% was the dominant management measure.

4 | DISCUSSION

Optimization algorithms are capable of identifying spatial configurations of management options that minimize trade-offs between

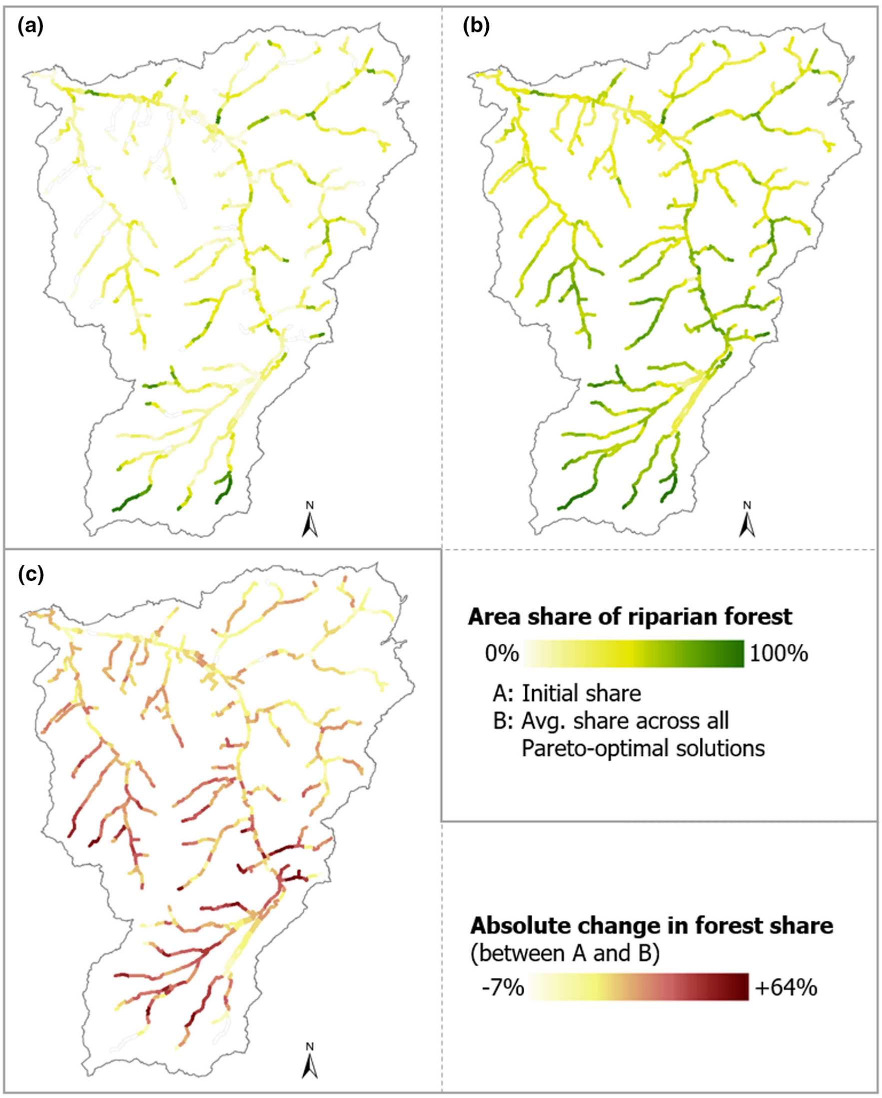

FIGURE 5 Spatial distribution of riparian forests in the riparian areas of the Zwalm catchment considering the initial share of forest in each riparian segment (a), the average share of riparian forests across all Pareto-optimal solutions (b), and the absolute change (c) in the share of riparian forests comparing the maps a and b

competing objectives and maximize synergies between noncompeting objectives. Accordingly, such algorithms and have been increasingly used to study the allocation of management options on the landscape scale, considering a variety of settings, land-use categories and landscape elements (Kaim et al., 2018; Lautenbach et al., 2013; Verhagen et al., 2018). With this study, we presented the first spatially explicit multi-objective optimization of riparian forests at a whole-catchment scale considering four, partly contrasting, objectives. We provided solutions for the design of a riparian optimization framework, addressing various challenges related to spatial set-up, model design and visualization that come along with the linear character and limited geographical scope of riparian areas. Our study also represents an example of how empirical biological research can provide the required knowledge for supporting stakeholders in decision-making processes like landscape planning and (aquatic) biodiversity conservation.

4.1 | Trade-offs and synergies in riparian landscapes

Our results showed significant trade-offs between agricultural production in riparian areas of the Zwalm River and indicators for ecosystem functioning and biodiversity. It became clear that a spatial mixture of forest management measures can be beneficial in mitigating existing trade-offs. The benefit of our optimization approach is that it did not only show that trade-offs exist, but also how these trade-offs could be best balanced through appropriate combinations of measures, which is an important information basis for landscape planners (Jones et al., 2013). The trade-offs between natural values and societal needs may be even more distinct when taking into account the area demand and value of other land-uses (e.g. urban, industrial), which we considered only indirectly by setting corresponding area constraints.

Synergies have been observed between steam ecological quality (EPT index) and slowed riparian carbon processing, which is expected to increase carbon permanence and sequestration potential (Matzek et al., 2020). Both target indicators benefitted to a comparable extent from an increase in riparian forests, possibly driven by a reduction of temperatures and soil nutrients (Johnson & Almlöf, 2016). This was not the case for the functional diversity of diatoms, which generally was less affected by forest increase and showed different demands regarding the allocation of reforestation measures. The outcomes indicate that careful target-setting is important as synergies and trade-offs will shift among varying sets of target indicators. Riparian restoration could also provide benefits for upland agricultural areas in terms of pollination, sedimentation control, surface runoff and water availability.

We found some solutions that showed benefits for all four target indicators at the same time, demonstrating that the overall multifunctionality of the riparian landscape could be increased. The benefits of these cases have been minor, which is also a result of the study design that did only allow for minor replacement of existing forest areas. More differentiation in the types of measures (e.g. forest types) may point out additional synergies that could not be identified in this study, but up to now, this lacks empirical foundation and applicability in large-scale modelling approaches.

4.2 | Landscape-scale planning of riparian forests

All target indicators within our study were sensitive to the landscape-scale configuration of riparian forests, including its total amount, connectivity and positioning in the river network. This confirms the findings of several other studies highlighting the importance of landscape configuration for the provisioning of ecosystem services (e.g. Lautenbach et al., 2011; Mitchell et al., 2015; Verhagen et al., 2016, 2018).

We found numerous optimal combinations of forest management measures in the Zwalm riparian corridor, which is typical for multi-objective optimization and makes it difficult to provide specific advice for spatial planning (Karakostas, 2017). Previous studies selected and visualized individual solutions along the Pareto-front, thus providing examples on how extreme land-use configurations, as well as compromises, could look like (Gourevitch et al., 2016; Pennington et al., 2017; Schwarz et al., 2020; Strauch et al., 2019). Furthermore, additional stakeholder preferences could be used to weight and prioritize specific solutions (Kaim et al., 2020). We focused our analysis on the identification of priority areas of specific measures, based on an aggregation of the whole Pareto-optimal solutions space (Karakostas, 2017; Verhagen et al., 2018). The advantage of this approach is that it allows for the direct identification of target areas and has the potential to inform policymakers and stakeholders. The spatially explicit information are easily accessible and allow for integration into planning processes. However, such a simplification of optimization results might mask out specific local trade-offs as well as other important considerations and can thus only be one element of the decision-making process. Political and economic constraints (e.g. implementation costs) can be considered at different stages of the planning process—prior, within or after the optimization procedures (Bartkowski et al., 2020; Kaim et al., 2018). Each approach has specific advantages for the identification of implementation pathways, but these aspects were beyond the scope of our study.

Looking at the full riparian corridor of the Zwalm River, we observed a preference for land-sparing related solutions, which means a preference for 'extreme' land-uses and their spatial separation (Phalan et al., 2011). Intensive reforestation of the riparian segments (ReFor100%) and a slight deforestation (DeFor20%) for the benefit of agricultural land covered together 61% of the Pareto-optimal solutions space. Land-sharing solutions that allow for both agricultural production and a moderate reforestation (20%–80%) in the same riparian segment were the minority. This also became visible in the regional preference of specific management options. Our results suggest that a considerable increase and connection of forest patches in the headwaters of the Zwalm River will be efficacious. On the other hand, the downstream parts of the catchment showed an increased placement of trade-off mitigation measures that reduce the extent of existing forest patches for the benefit of catchment-scale agricultural production. The dominance of the ReFor100% measure could also indicate the importance of a proper dimensioning of riparian forests (forest width > 50 m), which is in contrast to the single line of trees along the river that is often observed in agricultural landscapes like the Zwalm catchment. Overall, the large number of optimal forest allocation scenarios we identified can be a valuable basis for detailed insights into the study region, cross-sectoral learning formats and assist catchment-scale planning of reforestation measures.

4.3 | Limitations of the study and future research

Riparian areas provide a huge variety of values, functions and services that could not be taken into account within our assessment. As the results of any optimization depends a lot on the selected response variables, future studies should test the robustness of our findings considering additional target indicators. The optimization algorithm NSGA-II is most often used for solving spatial allocation problems, but is unfortunately restricted to a maximum of four objectives (Malczewski & Rinner, 2015). However, several other optimization algorithms exist that also allow handling of more than four objectives (Deb & Jain, 2014). Future studies might also enhance the pool measures that are considered for implementation, including a broader perspective on riparian restoration. In our study, riparian forest has been used as a homogeneous category without considering the type and age of trees or the condition of the riparian habitats provided (Burdon et al., 2020). Nevertheless, the consideration of complex types of measures requires not only specific models, but also detailed spatial data on the respective status quo for the whole riparian catchment of a study area, which is typically not available.

Any optimization framework depends on the quality of the underlying models used to calculate the individual target indicators. The CROSSLINK project made huge efforts to collect an extensive set of empirical data (Burdon et al., 2020; Forio et al., 2020; Kupilas et al., 2021) that allows for a quantification of the effects of forested riparian buffers not only on the local scale, but also along the river network. Nevertheless, predictive modelling of ecosystem variables across a whole riparian corridor remains uncertain and our statistical models were based on a rather small sampling size, thus not allowing for a robust model validation and uncertainty analysis. More sampling sites are needed that also cover a larger variety in the type of river sections and gradients along the stream to further improve the reliability and accuracy of our models. However, any environmental model and computational optimization requires a set of simplifications and assumptions and our optimization results present a successful proof of concept. Another simplification that might be reconsidered is the use of a fixed width for the definition of our riparian modelling units as the width of the active riparian zone is obviously very variable throughout a catchment. For modelling studies, the use of fixed spatial units is widespread as it enables applicability in different settings (Damanik-Ambarita et al., 2018), including urban surroundings, and covers in most cases the maximum amount of land that might be realistically open to management. For each of our modelling units (riparian segment), a set of explorative management measures was developed that involved different dimensions of reforestation and a width of 100 m did only represent its upper boundary (ReFor100%). However, depending on the selected target indicators, the relevant width might be larger (Dala-Corte et al., 2020; Luke et al., 2019) and can thus strongly affect results and trade-offs.

4.4 | Management recommendations

The study results can be used to assess the overall capability of riparian reforestation measures for improving stream–riparian attributes within the Zwalm catchment and the potential effects for ecosystem functioning and biodiversity are substantial. Nevertheless, other factors will likely restrict maximum recovery below feasible target values (Mouton et al., 2009) and accordingly riparian reforestation cannot be the only measure to improve the stream–riparian status quo. To improve the overall condition of the Zwalm River also morphological disturbances (e.g. weirs), urban wastewater input and impacts of the terrestrial land-use (e.g. agricultural runoff) in the whole catchment need to be considered. Furthermore, spatial and temporal legacy effects can reduce the efficacy of riparian rehabilitation and need to be considered when planning for successful forest restoration (Bernhardt & Palmer, 2011; Crouzeilles et al., 2016; Mika et al., 2010). Legacy effects are the consequence of historic disturbances that continue to influence environmental conditions long after the initial appearance of the perturbation (Allan, 2004). Spatial legacy effects can occur when impacts on riverine ecosystems are transmitted far from their point of origin (Palmer, 2010).

Regarding the effective use of reforestation measures in the Zwalm riparian corridor, our results show clear priorities for their allocation and required intensity. Some headwater regions of the Zwalm River are rather unpolluted and provide habitat for rare fish species and vulnerable macroinvertebrates (Boets et al., 2021; Soresma, 2000). Our optimization results suggest connecting existing forest patches in headwaters and to further expand them downstream. In doing so, a proper dimensioning of the riparian forests should be considered as our results show a significant preference for a rather intensive reforestation of the selected riparian segments. Nevertheless, care should be taken to not interpret our way of presenting the optimization results as a single best solution, but as a starting point to inform stakeholders and to encourage further discussions.

It became clear that the trade-off between natural and societal values in the riparian areas of the Zwalm is rather distinct. Gains in environmental target indicators have almost always been associated with losses in agricultural production. The optimization results showed the possibility to mitigate the negative effects on agricultural production to a small extent in the downstream sections of the Zwalm River, but the conversion of existing forests into agricultural land is not in line with actual legislations and policies. Instead, there is a need for multi-level and transdisciplinary dialogues and actor involvement to increase awareness on the environmental issues, related trade-offs and the acceptance of management measures in the Zwalm catchment.

5 | CONCLUSIONS

The analysis has shown that riparian reforestation in agricultural catchments can improve multiple indicators for ecosystem functioning and biodiversity. By applying a landscape-scale optimization algorithm on the placement of management measures, we have shown how to balance trade-offs with agricultural production and identified the headwater regions of the Zwalm catchment as priority regions for reforestation actions. Our approach can be transferred to different catchments and provides a valuable addition to scenario analysis and grounds for future biodiversity and ecosystem functioning assessments, which usually lack trade-off analysis (Lautenbach et al., 2019; Seppelt et al., 2013). A necessary next step would be the consultation with stakeholders and an in-depth analysis of regulations to incorporate policy constraints and to identify feasible pathways (Bartkowski et al., 2020).

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

F.W. and M.V. designed the research with contributions from all authors; F.W., M.A.E.F., F.B. and B.G.M. contributed to data gathering and model development; F.W. set-up the optimization framework and analysis with contributions from M.S. and M.V.; F.W. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Zenodo Digital Repository https://doi.org/10.5281/zenodo.6412402 (Witing et al., 2022).

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