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Using crushed waste bricks for urban greening with contrasting grassland mixtures: no negative effects of brick-augmented substrates varying in soil type, moisture and acid pre-treatment

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Abstract

Ecological restoration aims at supporting biodiversity and ecosystem services, and urban greening is a great opportunity to achieve this goal. This is facilitated by species-rich seed mixtures based on local provenances, which are designed for certain nutrient and moisture regimes based on functional plant traits. Such grassland mixtures might be cultivated on crushed waste bricks, which would be a new component of water-holding urban substrates. Thus, we studied the effects of brick quantity and quality, acid pre-treatment of bricks, soil type and moisture on biomass of designed seed mixtures. Three greenhouse experiments were conducted, with substrates consisting of different brick ratios (5% vs. 30%), brick types (clean production waste vs. demolition material), and brick treatments (acid vs. control) tested on three trait-based mixtures and a non-regional commercial standard mixture. The trait-based mixtures included information on specific leaf area, seed mass and grass-to-legume ratio. There were no negative effects of demolition bricks, soil texture and moisture on grassland biomass. Acid-treated clean porous bricks improved biomass production of the standard and intermediate mixtures, while the effect was minimal with demolition bricks. Designed seed mixtures had a biomass similar to the standard mixture under dry conditions but did not benefit from high moisture like the standard mixture. In conclusion, waste bricks are a useful additive for urban restoration substrates to save raw material, and specifically designed regional mixtures can replace commercial grassland types on these substrates.

Keywords Drought · Ecological restoration · Functional traits · Novel ecosystems · Recycled aggregates · Regional seed mixtures

Highlights

- Grassland mixtures grow successfully on substrates augmented with crushed bricks.
- Biomass production is unaffected by brick quantity and quality.
- Performance of trait-based seed mixtures matches commercial standard mixtures under dry conditions.

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Introduction

Re-using organic or mineral wastes as planting substrate is a promising way of recycling. This has been shown for construction waste, bricks, coal gangue, paper ash pellets and sewage sludge (Du et al. 2020; Liu et al. 2019; Molineux et al. 2015; Naeth and Wilkinson 2014). In China, 2,400 million tons of construction waste were produced in 2015 (Liu et al. 2019), and in Germany 215 million tons in 2016 (Kreislaufwirtschaft 2019). Waste materials have some potential to substitute soil in restoration practice, and thus to reduce the consumption of raw material, and to save costs (Walsh et al. 2018). In this study, we focus on crushed waste bricks which are available in large quantities, for example about 10 million tons in Germany in the 2014 (Umweltbundesamt 2019). Waste accumulates during brick production and through demolition of buildings.

Brick waste as a component of restoration substrates would be a valuable alternative to using waste bricks as bulk material for construction work, while demolition bricks with remains of mortar and plaster are rarely used as substrate component (Umweltbundesamt 2019). Bricks have a high water-holding capacity, while the pH of about 10 is rather high, increasing the pH of the substrate to 7–9 (Hitchmough et al. 2001; Molineux et al. 2009). A treatment with phosphoric acid might reduce the pH value and improve soil fertility. Thus, crushed clean bricks of up to 80% are used for green roofs (Molineux et al. 2015; Stovin et al. 2015), or in small quantities as planting substrate in gardens and landscaping. However, brick-augmented substrates with varying water holding capacity and different nutrient concentrations have not been tested for grassland restoration in comparison to standard topsoil (Molineux et al. 2009; Nagase and Dunnett 2010).

Crushed waste bricks as component of planting substrates can be used for landfill and quarry restoration as well as for road verges and urban greening, often resulting in 'novel ecosystems' (Hobbs et al. 2006; Kowarik 2011), while they might benefit biodiversity and ecosystem services (Bowman et al. 2017). Urban greening could accommodate considerable amounts of brick-augmented substrate to support semi-natural grasslands that otherwise have declined, for example in Central Europe (Poschlod et al. 2005; Wesche et al. 2012). So far, grass-dominated seed mixtures are used for urban greening that result in species-poor swards with few resources for pollinators (Hefter et al. 2010). Most seeds are of non-regional origin, i.e. they do not derive from local provenances. Therefore, these seed mixtures are less supportive for native biodiversity (Durka et al. 2017), while seeds for restoration should be regionally adapted to benefit long-term restoration success (Bucharova et al. 2019).

A topical issue in restoration ecology is reassembling plant communities that simultaneously foster biodiversity and specific ecosystem processes (de Bello et al. 2010; Funk et al. 2008). Biodiversity could benefit from species pools of semi-natural grasslands, with a high proportion of regional provenance herbs. However, for urban greening no specific seed mixtures have been tested that would fit brick-augmented substrates. Development of such mixtures could be assisted by recent progress in trait-based community ecology (Suding et al. 2008) that promotes functional restoration (Laughlin 2014).

The classic approach of this method is to adopt a candidate list of species deemed suitable by expert opinion. However, this approach is not general and therefore not transferable and comparable to less familiar conditions. In that respect, a suitable quantitative approach could be trait-based models sensu Laughlin (2014). Trait-based species selection can be transferred to new conditions, and outcomes can be more easily compared (Suding et al. 2008). However, unspecific regional seed mixtures suffer from environmental sorting which reduces seeding efficiency (Freitag et al. 2021), while using designed seed mixtures could reduce mortality risks of seedlings, leading to lower costs, higher functional outcomes and improved restoration success (Laughlin et al. 2017). More specifically, seed mixtures for brick-augmented substrates must be adapted to high pH and variable soil moisture. For example, species with a high specific leaf area (SLA) have high transpiration and high growth rates (Poorter et al. 2009). However, the response of SLA to environmental factors must be monitored, as it tends to be higher on nitrogen-rich soils and with increased moisture (Ordoñez et al. 2009; Poorter et al. 2009). Another promising functional trait is seed mass which tends to be higher under adverse site conditions (Westoby et al. 2002). On productive soils, graminoids are a major component (Feßel et al. 2016), whereas legumes are facilitative for non-legume plants (Erktan et al. 2018).

The aim of this study is to test the effects of brick-augmented substrates on contrasting seed mixtures under different moisture regimes. We established three full-factorial experiments to address the following questions:

1. How do grassland seed mixtures respond to substrates with different brick quantity and quality, and which effect have crushed bricks pre-treated with phosphorous acid?
2. Does a high brick ratio reduce negative drought effects on grassland biomass?
3. Do seed mixtures respond differently to soil moisture regimes on brick-based substrates?

Material and methods

Species and trait selection and community design

As test communities for assessing the quality of different brick-augmented substrates, we used lowland meadows growing on nutrient-rich moderately moist soil in Central Europe (Leuschner and Ellenberg 2018; Oberdorfer and Müller 1983). For the design of the seed mixtures, we excluded species with a rooting depth > 1 m (Kutschera and Lichtenegger 1982, 1992; Landolt and Bäumler 2010) and those that were not commercially available. From the remaining pool of 41 herbaceous species, twelve forbs, three legumes, and seven grasses were selected (Appendix, Table A1; the composition of the 20 species was randomly chosen for each plot.

We constrained the communities to certain forb-grass-legume ratios, to two traits (SLA, seed mass) and the Ellenberg R value. Three opposing seed mixture types were designed based on the pre-determined species compositions by adjusting the weight proportion of the seeded species. For the 'vigorous' type, we opted for high SLA, low seed mass, high grass ratio and low legume ratio (Table 1), the 'robust' type had opposing values, and the 'intermediate' type was in between. In addition, the mean Ellenberg R value was set to 7 for all mixtures to account for the relatively high

Table 1 Characteristics of the grassland seed mixtures based on seven functional traits which were obtained from databases. Values are community-weighted means according to species proportion by weight in the respective mixture. Species composition was randomly selected for each plot based on a species pool. 'Standard' is a non-regional seed mixture (Regel-Saatgut-Mischung RSM 7.1.2 *Landschaftsrasen mit Kräutern* DIN 18 917); seeding densities follow practical recommendations; SLA, specific leaf area

Seed mixture	SLA [$mm^2\ mg^{-1}$]	Seed mass [mg]	Grass ratio [wt%]	Legume ratio [wt%]	Forb ratio [wt%]	Ellenberg R	Rooting depth [cm]	Seeding density [$g\ m^{-2}$]
Robust	20.0	1.25	30.0	15.0	55.0	7.0	0–100	4
Intermediate	21.5	1.00	45.0	10.0	45.0	7.0	0–100	4
Vigorous	23.0	0.75	60.0	5.0	35.0	7.0	0–100	4
Standard	19.0	0.74	98.3	0.3	1.4	4.9	0–>200	20

pH of brick-augmented substrates. The used community-weighted means of the intermediate mixture were based on communities described by Oberdorfer and Müller (1983), as also seen in commercial mixtures of the company Krimmer (Appendix, Table A2).

To calculate the proportion of each species on the entire seed mass, the community-weighted means and the randomly selected species compositions were put into the function 'Select' of the package 'Select' (Laughlin 2014). Trays were seeded with a density of 4 g m^{-2} as recommended by Kirmer (2019). These designed seed mixtures were tested against a commercial standard mixture for non-agricultural grassland with 17 species and a density of 20 g m^{-2} (*Regel-Saatgut-Mischung* RSM 7.1.2 'landscape lawn with forbs' DIN 18917 2018). The R indicator values of plant species were taken from Ellenberg et al. (2001); the traits were available for 98–99% of the species from the TRY database (Kattge et al. 2020).

Experimental design

Brick-augmented substrates were tested in three experiments at the Greenhouse Laboratory Centre Dürnast, Technical University of Munich (WGS 84 (lat, lon): 48.40583, 11.69151). All treatment combinations were grown in plastic trays (50 cm × 30 cm × 6 cm). The loamy soil was provided by the company Wurzer Umwelt, and the brick rubble was production waste from modern, porous bricks (38% intra-particle pore space) of the company Leipfinger-Bader, while the demolition bricks produced in the 1960s have a lower rate of porosity (27% intra-particle pore space). The porosity of modern bricks is increased by adding sawdust to the raw material, which then burns in the kiln, leaving air voids. The demolition bricks were cleaned and sorted but still had remains of mortar and plaster, and all bricks were crushed to a fraction 4–16 mm.

The substrates with 5% bricks had pH values of 7.4 ± 0.1, and the ones with 30% pH 7.1 ± 0.5 (Table 2). The organic matter was reduced by bricks amounting in Experiments 1 and 2 to 5.4–8.4% and 0.9–3.9% in Experiment 3 (Table 2). Phosphate was significantly increased by acid-treated demolition bricks (134–548 mg 100 g^{-1}), but not by acid-treated clean bricks (15 mg 100 g^{-1}) (Table 2).

Experiments 1 and 2 started at the end of May 2019 and ran for 14 weeks in a semi-open greenhouse with a glass roof but with wire mesh walls so that climatic conditions were similar to outside conditions, with an average temperature of 19 ± 6 °C (www.dwd.de, accessed 27.02.2020; Appendix, Fig. A4). Experiment 3 started in mid-January 2020 and lasted 13 weeks in a heated closed greenhouse with a temperature of 20–22 °C during the day and a light supply of 70 µmol m^{-2} for 12 h d^{-1} (Appendix, Fig. A4). In Experiments 1 and 2, the trays were watered every day for the first four weeks from above, and after plant establishment they were watered from beneath. To induce a moisture gradient, water amount was the same per watering, but frequencies differed between blocks: every second day, daily, twice a day, or thrice a day. For Experiment 3, plants were watered on demand (every 5–8 days) to avoid water stress. In all experiments, non-seeded species were identified every second week and removed.

In total, 128 trays on eight tables were used in Experiment 1, and 64 in Experiment 2. Both experiments were full-factorial and had a split-plot design with a randomized complete block design on the plot level; plots were re-randomized after seven weeks. On the block level (= table), there was the treatment 'moisture' with two replicates, and on the plot level (= tray), Experiment 1 had three treatments with eight replicates. The treatments were four seed mixtures (standard, robust, intermediate, vigorous), two brick ratios of the substrate by volume (5%, 30%), and with or without acid treatment of the bricks with phosphoric acid (concentration of acid 0.3 mol kg^{-1}, added in concrete mixer with a retention time of 4 min); the bricks were clean production waste. In Experiment 2, the treatments on plot level were two seed mixtures (robust, vigorous), two brick ratios (5%, 30%), and two brick types (clean production waste, demolition bricks with plaster and mortar); all bricks were treated with phosphoric acid.

Table 2 Substrates used for the three experiments: Clean bricks were new porous crushed bricks; demolition bricks were old, low-porous bricks from the 1960s; acid treatment was done with a phosphoric acid (H_3PO_4; concentration of acid 0.3 mol kg^{-1}). Soil texture was classified according to the *Bodenkundliche Kartieranleitung* (Bundesanstalt für Geowissenschaften und Rohstoffe 2005). Since brick rubble was 4–16 mm, it did not affect soil texture of the fine soil; the proportions of fine sand and silt refer to the fine soil. The pH was measured in $CaCl_2$ solution for a soil sample of fine and coarse soil combined. Organic matter was measured from the ignition loss (550 °C). Plant available phosphorus and potassium were measured in a calcium acetate-lactate extract and magnesium in $CaCl_2$ extract (fraction < 2 mm). Further soil data in the Appendix, Table A3

Substrate	Brick type	Acid treatment	Soil texture	Fine sand [wt%]	Silt [wt%]	pH	Organic matter [wt%]	P_2O_5 [mg 100 g^{-1}]	K_2O [mg 100 g^{-1}]	Mg^{2+} [mg 100 g^{-1}]
Experiment 1										
Bricks 5% no acid	Clean	No	Slu	11	40	7.4	7.2	17	14	31
Bricks 30% no acid	Clean	No	Sl4	11	38	7.5	5.9	32	19	40
Bricks 5% with acid	Clean	Yes	Slu	11	46	7.5	8.4	52	45	34
Bricks 30% with acid	Clean	Yes	Slu	10	42	7.7	6.2	67	40	57
Experiment 2										
Clean bricks 5%	Clean	Yes	Slu	11	46	7.5	8.4	52	45	34
Clean bricks 30%	Clean	Yes	Slu	10	38	7.7	6.2	67	40	57
Demolition bricks 5%	Demolition	Yes	Sl4	13	16	7.1	6.6	15	12	24
Demolition bricks 30%	Demolition	Yes	Sl4	13	39	6.1	5.3	620	15	57
Experiment 3										
Loamy, 5% bricks	Demolition	Yes	Sl4	15	26	7.4	3.9	45	14	19
Loamy, 30% bricks	Demolition	Yes	Sl4	15	23	7.2	2.8	179	16	27
Medium 5% bricks	Demolition	Yes	Sl2	16	12	7.4	2.4	44	8	13
Medium 30% bricks	Demolition	Yes	Sl2	16	16	7.0	1.7	215	12	28
Sandy, 5% bricks	Demolition	Yes	Ss	17	6	7.3	0.9	40	4	12
Sandy, 30% bricks	Demolition	Yes	Ss	17	7	7.0	0.9	177	7	22

Experiment 3 had a full-factorial completely randomized design and was re-randomized three times with in total 72 trays. We established four treatments with three replicates: three soil textures (sandy, medium, loamy), two brick ratios (5%, 30%), and two substrate densities (low, high), and with or without pelletized activated carbon (1 t ha^{-1}). For the soil treatment, loam was mixed with 20, 50 or 80% quartz sand 0/4 (Table 2; Appendix Table A3).

Establishment of species ranged from 0 to 100% and was 73 ± 8% for species of the standard seed mixture, and 53–54 ± 5% for the designed regional seed mixtures in Experiments 1 and 2, and 71 ± 5% in Experiment 3 (Appendix Table A1). The species *Onobrychis viciifolia* emerged but could not establish and died.

Measurements and data analysis

The substrates were analyzed for grain size distribution, pH, nutrients and organic ratio (Table 2; Appendix Figs. A1, A2 and A3). In all experiments, grassland biomass was collected as a fitness indicator (Younginger et al. 2017) cut at 1 cm aboveground, while the fringe with a distance of 4 cm to the plastic edge was skipped to avoid edge effects. Then, the biomass was dried at 65 °C for three days and immediately weighed.

Due to right-skewed data distribution, biomass values were log-transformed. For Experiments 1 and 2, linear mixed-effects models were calculated with the random effect 'block' (= table) and the maximum likelihood method. For Experiment 3, a linear model was calculated. If the results were 'statistically clear' $p < 0.05$ (sensu Dushoff et al. 2019), we calculated contrasts with multiple comparisons and corrected them with the Tukey method. Uncertainties of the effects were expressed as standard error of the mean (SE).

The analyses were performed in R, version 4.0.2 (Team 2020) and with the packages 'Select' for community calculations (Laughlin et al. 2018), 'lme4' for liner mixed-effects models (Bates et al. 2015), 'MuMIn' for Pseudo-R^2 values (Barton 2019), 'DHARMa' for model evaluation (Hartig 2020), 'emmeans' for calculating contrasts (Lenth 2020), and 'ggeffects' (function 'ggemmeans') to extract coefficients for the graphs (Breheny and Burchett 2017; Lüdecke 2018).

Results

Experiment 1 showed that two seed mixtures had increased biomass on substrate with acid-treated crushed bricks (interaction: χ^2 (3) = 12.2, p = 6.9e–03; Fig. 1), i.e. the standard

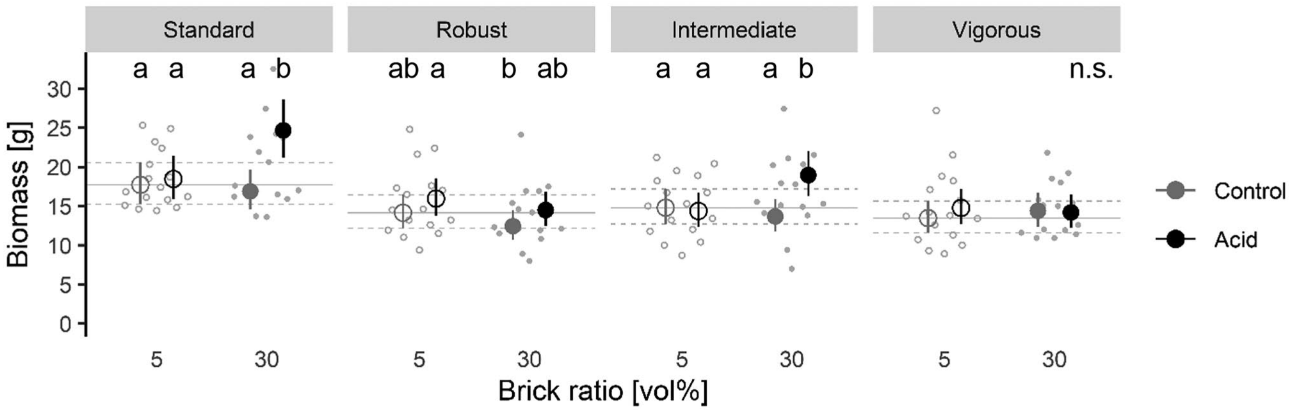

Fig. 1 Effects of acid treatment and brick ratio on biomass of four seed mixtures (cf. Table 1). For example, the effect within the standard mixture (5% control vs. 30% acid) +39 ± 13% SE, and within the intermediate mixture (5% control vs. 30% acid) +28 ± 12% SE (linear mixed-effects model: interaction: $p = 6.9e{-}03$). Shown are the estimated marginal means and the corresponding confidence intervals 95%. Letters indicate differences with $p < 0.05$ within each seed mixture. Data from Experiment 1 with new clean bricks

mixture (+39 ± 13%, compared to 5% bricks and no acid; $t_{1,155} = -3.6$, $p_{adj} = 2.2e{-}03$) and the intermediate mixture (+28 ± 12%, $t_{1,155} = -2.7$, $p_{adj} = 3.8e{-}02$). Furthermore, the vigorous and the robust mixtures showed an effect of <5%. Seed mixtures were differently affected by moisture regime (interaction: χ^2 (9) = 25.7, $p = 2.3e{-}03$; Fig. 5): the designed mixtures performed worse under moist conditions than the standard seed mixture (standard vs. intermediate: –29 ± 6%, $t_{1,155} = 3.8$, $p_{adj} = 1.4e{-}03$), but not under dry conditions (–1 ± 9%, $t_{1,155} = 0.1$, $p_{adj} = 9.9e{-}01$). Under all moisture regimes, the designed seed mixtures were not clearly different from the standard mixture under dry conditions: for example, robust seed mixture under medium moist conditions (–30 ± 16%, $t_{1,23.4} < -1.6$, $p_{adj\ (Dunnett)} = 6.5e{-}01$). Furthermore, the biomass of the designed mixes did not differ statistically clear under the different moisture regimes (all $t_{1,155} < |1.8|$, $p_{adj} > 2.6e{-}01$). Pseudo-R^2 values of the model for Experiment 1 were $R^2_{marginal} = 0.48$, $R^2_{conditional} = 0.71$.

Experiment 2 revealed that demolition bricks with a ratio of 30% had no effect on biomass (χ^2 (1) = 0.6, $p = 4.4e{-}01$, Fig. 2). Though, clean bricks reduced biomass by 7 ± 6% and demolition bricks by 25 ± 4% compared to the group with 5% clean bricks. Under any moisture regime, brick addition did not have a statistically clear influence on biomass production (interaction: χ^2 (3) = 7.1, $p = 6.8e{-}02$; Fig. 3): the brick effect reached from –8 ± 6% (dry) to +13 ± 7% (moist). Pseudo-R^2 values of the model for Experiment 2: $R^2_{marginal,} = 0.28$, $R^2_{conditional,} = 0.65$.

Experiment 3 showed that brick ratio had under any soil texture no effect on biomass: ($F_{2,59} = 0.1$, $p = 8.6e{-}01$; Fig. 4; $R^2_{adj} = 0.41$): for loamy substrate +23 ± 20% ($t_{1,59} = 1.3$, $p = 2.1e{-}01$) and for sandy substrate +8 ± 18% ($t_{1,59} = 0.4$, $p = 6.6e{-}01$) (Fig. 5).

Discussion

Acid-treated clean porous crushed bricks had a positive effect on the standard and the intermediate seed mixture, and no negative effect on the other two mixtures. There was no longer a positive effect if demolition bricks were used but also no negative effect. A brick ratio of up to 30% did not reduce the drought effect by sandy soils or few watering. The old, less porous bricks had no negative effect on biomass production. The trait-based seed mixtures were similar productive compared to standard seed

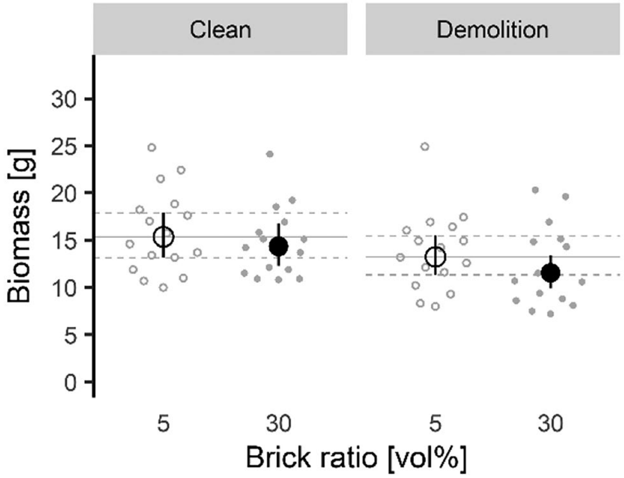

Fig. 2 No statistically clear effect of brick type and brick ratio (linear mixed-effects model: interaction: $p = 4.4e{-}01$). The effect of brick type on biomass (5% clean bricks vs. 30%), i.e. clean bricks 7 ± 6% SE, and demolition bricks –25 ± 4% SE. Shown are the estimated marginal means and the corresponding confidence intervals 95%. Data from Experiment 2 with the seed mixtures ‘vigorous’ and ‘robust’; all bricks were treated with acid

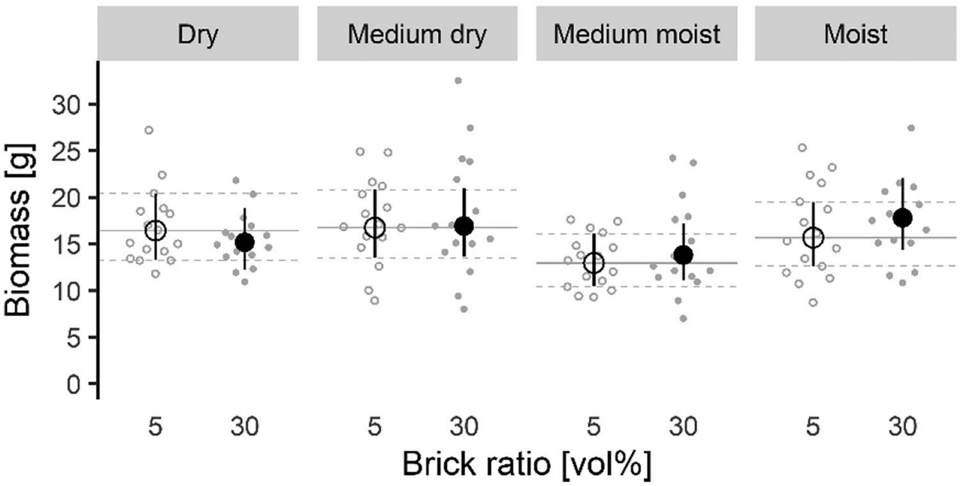

Fig. 3 The effect of brick ratio on biomass under different moisture regimes was not statistically clear (linear mixed-effects model: interaction: $p = 6.8\text{e–}02$). The effect ranged from −8 ± 6% SE (dry) to +13 ± 7% SE (moist) Shown are the estimated marginal means and the corresponding confidence intervals 95%; data from Experiment 1 with new clean bricks

mixtures under dry conditions. There was no difference in biomass among the contrastingly designed mixtures.

Effects of brick ratio, brick type and acidic pre-treatment on vegetation

To our knowledge, this is the first study that systematically tested an acid treatment of crushed bricks for planting substrates. We expected a positive effect of this treatment by lowering the pH level and by increasing phosphorus concentration. Although, the pH level was not affected significantly by acid in Experiment 1, and phosphorus was increased especially in substrates with demolition bricks in Experiment 2 (Table 2). This higher phosphorus content of demolition bricks may be the result of the reaction of phosphorus acid with the adherent mortar producing a higher amount of available Calciumphosphate compounds. In any substrate, plant-available phosphorus was present in sufficient quantities of more than 40 mg per 100 g soil (Table 2). Moreover, the substrate which had a positive effect on biomass production in Experiment 1 (acid-treated clean bricks), had a slightly increased amount of phosphate compared to the substrates with acid-treated demolition bricks which had no strong positive effect on biomass production (Table 2).

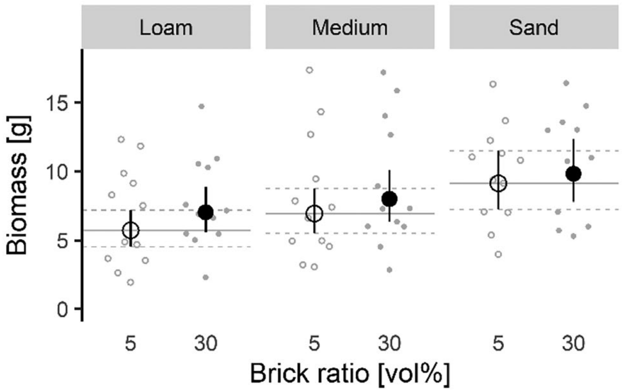

Fig. 4 No effects of soil type and brick ratio on biomass of the intermediate seed mixture (linear model: interaction: $p = 8.6\text{e–}01$). The effect ranged from +8 ± 18% SE (sand) to plus +23 ± 20% SE (loam). Shown are the estimated marginal means and the corresponding confidence intervals 95%. Data from Experiment 3 where the seed mixture 'intermediate' and the brick type 'demolition' were compared

Nevertheless, we could observe in Experiment 1 a statistically clear acid effect on biomass for substrates with clean bricks and the seed mixtures intermediate (+28%) and standard (+39%). However, this effect could not be reproduced in Experiment 3, with acid-treated demolition bricks especially when added to sandy soil. The main differences were an even lower moisture than the dry conditions in Experiment 1 with nutrient-poor soils. Experiment 2 showed a significant negative effect of demolition bricks compared to 5% clean bricks. This fits to the results of Hitchmough et al. (2001), who found a negative effect of brick-augmented substrate (50% demolition brick ratio) on biomass of seedlings of calcareous grassland species (−80–90%). The differences of demolition brick substrate to clean brick substrate were the pH value (6.2 vs. 7.7), the phosphate amount (600 vs. 67 mg 100 g^{-1}), and the amount of potassium oxide (14 vs. 40 mg 100 g^{-1}). However, in Experiment 3, demolition bricks had no longer a negative effect.

The pH value of bricks used in our experiments (clean: 8.2, demolition: 6.9) was lower than in other studies (Hitchmough et al. 2001; Molineux et al. 2009). Adding the non-acid treated bricks to soil resulted in pH values of the substrates of 7.5, which is similar to the substrate with only 5% bricks (pH 7.4). The pH can be reduced to around 8 by adding 15–20% compost (Ondoño et al. 2016), while adding 25% compost did not further change the pH value (Molineux et al. 2009). Hitchmough et al. (2001) could not reduce the pH value by adding 50% sand with a pH of 6.8 to demolition bricks. We observed a maximum reduction of the pH value by 0.4 after adding 30% demolition bricks to sandy soil. The sandy substrate still contained 14% topsoil and 0.9% organic matter in contrast to the substrate of Hitchmough et al. (2001). This suggests that organic material can buffer the pH of bricks very efficiently.

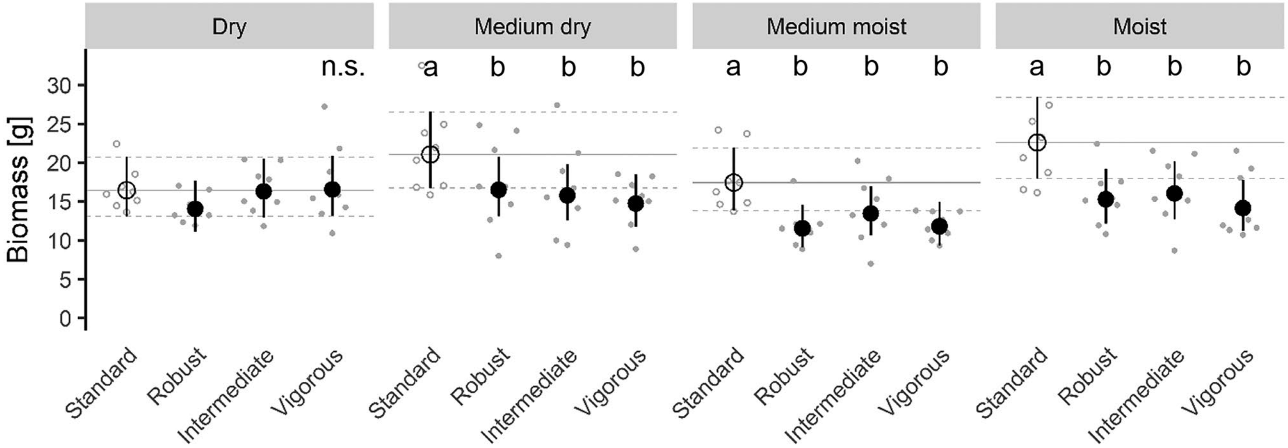

Fig. 5 Effect of soil moisture on biomass of the four seed mixtures (cf. Table 1), i.e. dry (standard vs. intermediate mixture) 1 ± 9% SE, and moist −29 ± 6% SE (linear mixed-effects model: interaction: $p = 2.3\text{e}{-}03$). Shown are the estimated marginal means and the corresponding confidence intervals 95%. Different letters indicate differences with $p < 0.05$ within each moisture regime. Data from Experiment 1 with new clean bricks

Do bricks reduce drought effects?

Crushed bricks should improve substrates by their high water-holding capacity (UBA 2018). High water holding capacity of the substrate is important for vegetation during drought periods (Farrell et al. 2012; Molineux et al. 2015). For brick-augmented roof substrates, water holding capacity seems to be more important than pH differences for species establishment (Molineux et al. 2015).

Our results showed no effect on biomass after brick addition under dry conditions in Experiment 1, which suggests no significant difference in water holding capacity between the used loamy soil and bricks. The available water capacity is affected by soil type, storage density and humus amount (Bodner et al. 2015). Therefore, we tested soil types from loam to sand under dry conditions in Experiment 3, and found that there is no difference with or without brick addition. This would mean that bricks can substitute different soil types without a significant decrease in vegetation biomass. For drought resistance, the humus ratio seems to be more important (Graceson et al. 2014), and that humus is mixed in and not lying on top of the substrate (Schröder and Kiehl 2021). An advantage of demolition bricks is that they could emaciate humid soil and keeps water holding capacity compared to an emaciation by gravel. Nevertheless, the water holding capacity of the substrate results from the available water capacity and the substrate depth (Bodner et al. 2015). Further experiments should be conducted in the field with deeper substrates.

Effect of moisture on designed seed mixtures

In ecological restoration, seed mixtures are wanted that simulta neously improve biodiversity and ecosystem services (Bowman et al. 2017). Here, a trait-based approach allows greater generality for species compositions and more predictive power (Shipley et al. 2016). Designing trait-based seed mixtures could make seeding more efficient since general seed mixtures are filtered by environmental conditions like soil fertility. To our knowledge, these are the first results on a variety of species compositions and more than ten species to test trait-based models for restoration seed mixtures (cf. Laughlin et al. 2017; Yannelli et al. 2018). This shows that it is possible to establish species-rich seed mixtures that are resilient to dry or moist conditions. However, we could not create different outcomes under varying moisture regimes for the different seed mixtures in Experiment 1. The reason could be that the designed differences in community-weighted means were too low. Finding appropriate traits and mean trait values is a key challenge for trait-based restoration (Laughlin et al. 2017). In future, specified traits should be reduced and remaining traits discriminated or explicitly diversified with the function, and (long-term) field experiments would help with upscaling. First, the established vegetation did not sufficiently represent the seed mixture because some species would have emerged only after more than 13 weeks. An extension of the greenhouse experiment was not possible, because the trays were completely rooted. Second, different seed weights might not lead to the same proportions in dominance.

In comparison to the non-regional standard seed mixture, the designed seed mixtures had a similar biomass under dry conditions, although they were sown at lower density (4 g m^{-2} vs. 20 g m^{-2}). Lower seed density especially of grasses improves establishment of all species also with lower competition ability in early life stages and therefore foster biodiversity (Dickson and Busby 2009). For practical amplification, it is not necessary to reach a maximum of productivity to keep management costs low, but coverage should be enough to fulfill ecosystem functions like soil erosion. In our experiments, most designed seed mixtures approached the biomass of the standard mixture under dry conditions. These findings suggest that regional seed mixtures with a lower sowing density provide a sufficient quality for urban greening.

Conclusion

The greenhouse experiments revealed that grassland communities develop on brick-augmented substrates under different soil moisture without any negative effects on biomass. The results were consistent both for a standard seed mixture and three trait-based mixtures of regional origin. Further, the results suggest that crushed bricks could be successfully added to varying soil types, and a pre-treatment of the bricks with phosphorous acid seems unnecessary for community establishment. Thus, waste bricks are a promising component of new restoration substrates. However, to check for the large-scale effect of the water holding capacity of these novel substrates, field experiments are necessary.

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Authors' contributions MB and JK designed the study. All authors designed the substrates, and MB and JK the regional seed mixtures. MB set up the experiments, conducted data sampling, performed the statistical analyses, and wrote the manuscript. VH pre-treated demolition bricks, and MK developed and conducted the acid treatments. MB wrote the manuscript, and JK, MK and VH substantially contributed to various revisions.

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Declarations

Ethics approval We approve to comply the ethical standards.

Consent to participate Not applicable.

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