Article (refereed) - postprint

Chytry, Milan; Wild, Jan; Vojtech, Jarosik; Dendoncker, Nicolas; Reginster, Isobelle; Pino, Joan; Vila, Montserrat; **Maskell, Lindsay**; Kuhn, Ingolf; Spangenberg, Joachim; Settele, Josef. 2012 Projecting trends in plant invasions in Europe under different scenarios of future land-use change: policy orientations will not reduce invasions. *Global Ecology and Biogeography*, 21 (1). 75-87. 10.1111/j.1466-8238.2010.00573.x

Projecting trends in plant invasions in Europe under different scenarios of future land-use change

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Running title: Projecting future plant invasions in Europe

Abstract

Aim Recent studies of plant invasions in habitat types across different climatic regions of Europe made it possible to produce a European map of plant invasions. Parallel research led to the formulation of integrated scenarios of future socio-economic development, which were used to create spatially-explicit scenarios of European land-use change for 21st century. Here we integrate these two research lines and produce the first spatially explicit projections of plant invasions in Europe for the years 2020, 2050 and 2080.

Location European Union (except Bulgaria and Romania), Norway and Switzerland.

Methods We used vegetation plot data from southern, central and north-western Europe to quantify mean levels of invasion by neophytes (post-1500 alien plants) for forest, grassland, urban, arable and abandoned land. We projected these values on the land-use scenarios for 2020, 2050 and 2080, and constructed maps of future plant invasions under three socio-economic scenarios assuming (1) deregulation and globalization, (2) continuation of current policies with standing regulations and (3) a shift towards sustainable development.

Results Under all scenarios increase in the level of invasion was projected especially for north-western and northern Europe and decrease for some agricultural areas of eastern Europe where abandonment of agricultural land is expected. However, a net increase in the level of invasion over Europe was projected under all scenarios.

Main conclusions The polarization between more and less invaded regions is likely to increase if future policies are oriented on economic deregulation, which may result in serious future problems in some areas of Europe. However, an implementation of sustainability policies would not automatically restrict the spread of alien plants. Therefore invasions require specific policy approaches beyond the more general ones, which are currently on the policy agenda and were tested in the scenarios.

Keywords

ALARM scenarios, biological invasions, environmental change, habitat types, neophytes, non-native species, risk assessment.

INTRODUCTION

Human-mediated spread of alien species is a significant component of global environmental change (Vitousek, 1994; Sala *et al.*, 2000; Millenium Ecosystem Assessment, 2005) with serious impacts on biodiversity, economy and human health (Mack *et al.*, 2000; Vilà *et al.*, 2009; Perrings *et al.*, 2010). Invasions are closely associated with other components of global change such as climate change, land eutrophication, elevated atmospheric CO_2 concentrations or land-use change (Vilà *et al.*, 2006; Walther *et al.*, 2009). However, the use of habitat types or land-use categories for invasion risk assessment has scarcely been explored in spite of the fact that species spread is largely determined by other components of global change beyond climate (Ibáñez *et al*., 2008). Recent studies of plant invasions performed at a regional scale but with fine spatial resolution (within areas < 1000 m^2) revealed that the proportion of the number of aliens to all plant species is mainly determined by habitat types and much less so by the direct effect of climate, although climate does play a role in fine-tuning the habitat-related patterns (Chytrý *et al*., 2008a). This suggests that future regional trends in alien plant invasions will be mainly driven by land-use changes, which are associated with alterations of habitat types, disturbance regimes and rapid changes of species composition (Hobbs, 2000).

European studies focusing on the relationship between habitat types and the level of plant invasion (i.e., number or proportion of species that are aliens; Lonsdale, 1999; Richardson & Pyšek, 2006; Chytrý *et al.,* 2008a) revealed that the same habitat types contain similar proportion of alien plant species in oceanic, subcontinental and Mediterranean regions (Chytrý *et al.,* 2008b). This remarkable consistency within habitats across regions made it possible to project data on the mean levels of plant invasion in a range of European habitats on land-cover maps and produce the first European map of the level of invasion by alien vascular plants (Chytrý *et al.,* 2009a). However, the development of effective strategies for the management of alien plant species requires additional information on possible future trends.

Recently developed scenarios of future land-use change for Europe (Reginster & Rounsevell, this issue) provide a suitable platform for projecting spatially explicit trends in future levels of plant invasion. These land-use scenarios were generated by models which used input parameters from three storylines, i.e. qualitative and partly semi-quantitative descriptions of possible futures, resulting from an analysis of socio-economic processes (Spangenberg 2007; Spangenberg *et al.*, this issue). At the same time, these models were linked to other models based on the same storylines (i.e. having the same assumptions), which made it possible to assess the effect of future global trade and climate change on European land use.

In this paper, we link the two previously separated research lines, one on the plant invasions in different habitats and the other on scenarios of future land-use changes. For the first time, we (i) develop maps of possible future patterns of alien plant invasions across Europe for three socio-economic scenarios representing different emphasis on economic growth, and (ii) assess and compare the levels of invasions and their geographical pattern under these scenarios to find out how they are likely to translate into future problems with invasive alien plants in Europe.

MATERIALS AND METHODS

ALARM scenarios

In this study we use recently developed spatially explicit scenarios of the future land-use in Europe for the years 2020, 2050 and 2080 (Reginster & Rounsevell, this issue) to project possible future trends in the level of plant invasion across the continent. These scenarios were developed within the EU project ALARM ("Assessing LArge-scale Risks for biodiversity with tested Methods"; Settele *et al*., 2005) as a result of combined qualitative and semi-quantitative analyses of possible futures with model runs.

The first part of the scenario development was a formulation of storylines (or narratives; Alcamo, 2001). Three core storylines were developed within ALARM, describing three internally consistent alternative scenarios of future socio-economic development, which reflect different policy options currently discussed in the European Union (Spangenberg *et al.*, this issue). As each scenario involved a large number of assumptions, they were developed in two steps. First, the overall policy trajectories were defined and checked with current decision makers whether these were relevant from their point of view. Then the policies expected in different policy fields (based on, e.g. the EU Lisbon strategy, the EU Sustainable Development Strategy and the Biodiversity Action Plan) were formulated and discussed again with decision makers regarding the comprehensiveness, plausibility and coherence.

It is important to note that scenarios are not predictions, because the future cannot be predicted. Neither it is possible to calculate the probability of realization of alternative scenarios nor to validate the scenarios before the future happens. Scenarios simply illustrate possible future situations by making assumptions and examining what would happen if they turn out to be correct (Alcamo, 2001; van der Sluijs, 2002).

The three core ALARM scenarios, described in the storylines (Spangenberg *et al.*, this issue), are the following:

GRAS: *GRowth Applied Strategy* scenario supposes that economic and political paradigms of deregulation and globalisation will mainly determine future decision making, whereas biodiversity and sustainability policies will have little effect on the decisions. Environmental policies will focus on damage repair and limited prevention. The European Spatial Development Perspective (ESDP) will not be applied, which will result in expansion of urban areas. Subsidies provided as a part of the Common Agricultural Policy (CAP) will be removed and arable land will be only maintained in areas where it is profitable. Current protected areas will be preserved, but the Natura 2000 network will not be enforced.

BAMBU: *Business-As-Might-Be-Usual* scenario is based on the assumption that current policy trajectories (including regulations) will be implemented by the EU member states. Environmental policy will include climate change mitigation and adaptation measures. ESDP will be applied, and consequently peri-urbanisation in rural areas will be limited. CAP will be maintained, but overproduction will be avoided. Agriculture will be supported in areas where it is profitable and to some extent in other traditional rural areas (“disadvantaged areas” in EU parlance). The Natura 2000 network will be enforced. SEDG: *Sustainable European Development Goal* scenario combines what is considered necessary from a sustainability and biodiversity point of view, and desirable from a social and political perspective. It aims at competitive economy, healthy environment and international cooperation. Urban sprawl will be restricted, extensive agricultural management and organic farming will be supported, and agriculture will be maintained across the landscape by subsidising it in less productive areas. The Natura 2000 network will be extended and enforced.

Land-use projections

For each of the three ALARM scenarios (described in the storylines), each of the three target years (2020, 2050 and 2080) and for baseline data, which correspond to the situation in the year 2000, proportions of land-use categories were projected in grid cells of 10’ × 10’ (roughly 12 km × 18 km in Central Europe) in the countries of the European Union plus Norway and Switzerland. Romania and Bulgaria were not considered because they joined the European Union after the completion of the modelling project. This modelling was performed using MOLUSC ("MOdel of Land Use SCenarios"), an automated generator of land-use scenarios (Reginster & Rounsevell, this issue). The model input parameters were set based on the interpretation of the three storylines. MOLUSC was linked with a global macro-economic model (GINFORS; Stocker *et al.*, this issue) and a global ecosystem model (LPJmL; Bondeau *et al.*, 2007). In such a way, the land-use scenarios included the effects of global socio-economic factors, such as world population and international trade, on the future socio-economic situation in Europe (summarized in GINFORS) and about the effects of climate change on European agriculture (summarized in LPJmL), all based on the same assumptions.

Nine land-use categories were distinguished in MOLUSC: forest, grassland, urban areas, arable land, permanent crops, liquid biofuel plantations (e.g. oil-seed rape or sunflower), non-woody biofuel plantations (e.g. *Sorghum* or *Miscanthus*), woody biofuel plantations (e.g. willow, poplar or eucalypt) and abandoned land. We merged permanent crops with arable land, because the level of invasion is similar in these two categories (Chytrý *et al.,* 2008b). The area of biofuel plantations is expected to increase across Europe (Tuck *et al.,* 2006; Spangenberg & Settele, 2009), but currently there are no data on the level of invasion by alien plants in those biofuel crops that have not been traditionally planted in Europe. However, as the agricultural management of non-woody and liquid biofuel crops will correspond to that of traditional crops (many of them being also potential biofuels, e.g. cereals, potato or sugar beet; Tuck *et al.,* 2006), and therefore the level of invasion will probably be similar to that of the traditional arable land, we also merged these two biofuel land-use categories with arable land. Finally, there is little data on the level of invasion in plantations of potential woody biofuel crops, but the data from deciduous tree plantations indicate that these levels are close to those recorded for arable land (Chytrý *et al.,* 2005). Therefore the category of woody biofuel plantations was also included in the category of arable land. Thus we used five broad land-use categories, distinct in terms of the level of invasion: forest, grassland, urban areas, arable land and abandoned (surplus) land.

Data on the level of invasion and their projection on the land-use scenarios

By the term *level of invasion* we mean the number or proportion of plant species that are alien in a given habitat or at a site (Richardson & Pyšek, 2006; Chytrý *et al*., 2008a, b). This term is different from *habitat invasibility*, which is the habitat's susceptibility to invasion imposed by abiotic and biotic constraints under the assumption of constant propagule pressure (Lonsdale, 1999). This implies that a habitat with low invasibility due to its inherent properties can be highly invaded if the propagule pressure in a given site is high and *vice versa*. Our estimation of the levels of invasion for particular habitat types and land-use categories is based on the proportion of the number of neophytes, i.e. those aliens that arrived to the target area after A.D. 1500 (Pyšek *et al.,* 2004), and relates to local scale (areas < 1000 m^2; Chytrý *et al*., 2009a, b). We used proportions of total species numbers rather than absolute species numbers, because absolute numbers of alien and native species are positively correlated on large scales (Kühn *et al.*, 2003; Pino *et al.*, 2005; Stohlgren *et al.*, 2005); thus the large-scale pattern of the absolute numbers of neophytes would be similar to the pattern of total or native species richness.

In a previous study (Chytrý *et al.,* 2008b) the level of plant invasions at a local scale in 33 European habitats was assessed using 52,480 vegetation plots from phytosociological or landscape monitoring survey in Catalonia (NE Spain), Czech Republic and Great Britain (Schaminée *et al.*, 2009). These plots were sampled since the 1970s and ranged in size from a few m^2 to a few hundred m^2. Habitats were defined according to the European Nature Information System (EUNIS) classification (Davies *et al.*, 2004). This study revealed a striking consistency in the level of invasion of the same habitats among different regions, which justified extrapolation of the data from these three countries to other European regions where data were not available.

To obtain the mean value of the local level of plant invasion for each of the five land-use categories defined above, we transferred the EUNIS habitat types to those categories. As each of them corresponds to more than one habitat type, we estimated the proportional contribution of each EUNIS habitat type to each of the land-use categories in different European regions (Appendix S1 in Supporting Information). This estimation was based on the cross-tabulation of the EUNIS habitats and CORINE land-cover classes (Chytrý *et al.*, 2009a), interpretation of the five land-use categories used here in terms of the CORINE land-cover classes (Bossard *et al*., 2000), and proportional representation of each CORINE land-cover class in each region. For the Mediterranean areas, we made separate interpretations for irrigated and non-irrigated arable land because of a much higher level of invasion in the former (Chytrý *et al.,* 2009a). A special problem was the interpretation of the category of abandoned land, which can include very different vegetation types, ranging from recently abandoned arable land with weed vegetation to grasslands in the middle successional stages and forests at sites abandoned for a long time. In the extra-Mediterranean areas we also considered the late successional stages such as broad-leaved forests, but in the Mediterranean areas, only herbaceous and shrubland vegetation types were assigned to this category because of slower rate of succession in this summer-dry part of Europe (Escarré *et al*., 1983; Bonet & Pausas, 2004).

As in the previous study, which mapped current levels of plant invasion in Europe (Chytrý *et al.,* 2009a), we extrapolated quantitative data on the level of invasion from Catalonia, the Czech Republic and Britain to wider areas of Europe within the limits of European biogeographical regions (European Topic Centre on Biological Diversity, 2006, http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=839) as follows: (1) for the Mediterranean region we used the Catalonian data; (2) for the Continental and Pannonian regions, including embedded patches of the Alpine region, we used the Czech data; (3) for the British Isles we used the British data; (4) for the remaining part of the Atlantic region and for the Boreal region, including the embedded patches of the Alpine region, we used average values obtained from British and Czech data. We believe these mean values provide a reasonable approximation for the areas of Atlantic region on the European continent due to their transitional biogeographical position between oceanic and subcontinental climates, and also for the Boreal region, because Scottish and Czech mountains contain most of the habitat types typical of the Boreal region, such as coniferous forests, alpine grasslands and mires.

For each cell of 10’ × 10’ in each scenario, we plotted the weighted mean of the levels of invasion for land-use categories occurring in that cell, where weights were percentage areas of the cell occupied by the particular land-use categories. Weights for irrigated or non-irrigated arable land in the Mediterranean bioregion were adjusted according to the proportion of these two land-cover types in the CORINE land-cover map of Europe (Moss & Wyatt, 1994; Bossard *et al.,* 2000; version 8/2005 obtained from the European Environment Agency).

The level of invasion was visualized using four categories: < 1; 1–3; 3–5; > 5% of alien (neophyte) species. Boundaries of the categories were set up arbitrarily to allow for optimum visualisation. All GIS analyses and map visualizations were done in the ArcGIS 9.2 program (http://www.esri.com).

Statistical analysis

In statistical comparisons, individual grid cells were the units of observation. To allow for autocorrelation among the grid cells, all statistics were fitted as generalized least-square models with spatially correlated errors because these models appeared more parsimonious based on the Akaike information criterion (AIC; Burnham & Anderson, 2002) than models with spatially independent errors. Models with different assumptions about the correlated errors were compared, and the model with a rational quadratic description of spatial autocorrelation, which had the lowest AIC value, was chosen for description of the shape of spatial autocorrelation (Crawley, 2002: 723–729; Legendre & Legendre, 1998: 728–731). The resulting generalized least-square models thus do not violate the statistical assumption of independently and identically distributed errors and include corrections for pseudoreplications resulting from spatial autocorrelations (Rangel *et al.*, 2006; Dormann *et al.*, 2007)

The relationship between the occurrence of species that are included among the 100 worst invasive species in Europe in the DAISIE database (Lambdon *et al.*, 2008; DAISIE, 2009) and the mean level of invasion in grid cells was examined by linear regression. As the DAISIE database contains data on species occurrences in larger grid cells (50 km × 50 km) than used for the projections of land use and the level of invasion, mean levels of invasion for the 10’ × 10’ grid cells contained within each 50 km × 50 km grid cell were used for this analysis. Percentage of invasive species from the DAISIE database in the 50 km × 50 km grid cells was the response variable and the mean level of invasion in the same grid cells for the baseline data of 2000 the explanatory variable.

Temporal trends in the level of invasion were examined by analysis of covariance (ANCOVA). Mean levels of invasion in each grid cell for the three target years and positive or negative differences in each grid cell for the three target years relative to the 2000 baseline were the response variables, the three scenarios were factors, and the three target years were covariates. To test for non-linear components in temporal trends, square powers of target years were added to the models. Differences among the temporal trends were tested by deletion tests on common slopes of temporal trends for all three target years in minimal adequate models, in which all parameters were significantly different from zero and from one another, and all non-significant parameters were removed (Crawley, 2002).

Scenarios were examined by linear mixed-effect models using the same response variables as those which were used in ANCOVAs. Scenarios were a fixed factor, and target years a random factor nested within scenarios (Crawley, 2002: 723–729). Significant differences among all scenarios were tested by ANOVA and significant differences between the individual scenarios by least square difference (LSD) tests (Sokal & Rohlf, 1995: 240–260).

To normalize the data, the percentage of invasive species from the DAISIE database in each grid cell was angular transformed (Sokal & Rohlf 1995: 419–422) and mean level of invasion ln + 0.5 transformed (Yamamura, 1999), and positive and negative differences relative to the baseline $x^{0.1}$ transformed, based on Box-Cox series of transformations (Sokal &

Rohlf, 1995: 417–419). All models were checked by plotting normalized residuals against fitted values, by normal probability plots and by inspection of variograms for normalized residuals (Crawley, 2002: 726–729). All calculations were done in S-PLUS 8.1.1 (TIBCO Software®).

RESULTS

The highest levels of alien plant invasions among the five land-use categories (Table 1) were projected for arable land, followed by urban areas and abandoned land. In the Mediterranean areas irrigated arable land was projected as much more invaded than dry arable land. In the British Isles a high level of invasion was also projected for forests.

The map of the level of invasion for the baseline of 2000 (Fig. 1) projected the highest levels of invasion in lowland areas of western, central and eastern Europe and some agricultural areas of southern Europe. Low levels of invasion were mapped in the boreal and arctic zones, areas with extremely oceanic climate, mountain areas across the continent, and Mediterranean areas that are not used for intensive agriculture. There was a strong positive relationship ($F_{1, 2370} = 57.63$, $P < 0.0001$) between the mean level of invasion in 50 km × 50 km grid cells (Fig. 1) and the percentage of the total number of the invasive plant species that are included among the 100 worst invasive species in Europe and occur in these cells.

Projected patterns of the level of invasion in 2020, 2050 and 2080 across Europe are not dramatically different from the baseline under any of the three scenarios (Figs. 2–4). Still there are clear trends in the level of invasion under different scenarios and for different time periods. Both changes in temporal trends for the three years (deletion test on mean levels of invasion, mean increases and decreases per grid cell, respectively: $F_{4, 265383} = 10.48$, $F_{2, 124468} = 249.56$, $F_{2, 65586} = 37.83$, all $P < 0.0001$) and among the scenarios (ANOVAs on mean levels of invasion, mean increases and decreases per grid cell, respectively: $F_{2, 265383} = 33.40$, $F_{2, 124468} = 790.0$, $F_{2, 65586} = 7768.0$, all $P < 0.0001$) are statistically significant.

Under the GRAS scenario (Fig. 2), both increases and decreases in the level of invasion were projected, the former being smaller but increasing continuously from the baseline to 2080 (Fig. 5b). The strongest increases were projected for Ireland, the Netherlands and some other areas of north-western and northern Europe where current levels of invasion are low or average. In contrast, decreases in the level of invasion were projected for the agricultural areas of eastern Europe, namely the Baltic countries, Poland and Hungary, western-central

Europe and also some parts of south-western Europe, such as coastal areas and south-western France. The mean projected level of invasion per grid cell is significantly lower under GRAS than under BAMBU and SEDG scenarios, which do not differ significantly, although their temporal trends differ (Fig. 5a).

Under the BAMBU scenario (Fig. 3), projected spatial patterns of increases and decreases in the level of invasion follow similar trends as under GRAS. However, under BAMBU significantly smaller decreases and higher increases were projected than under GRAS by 2080 (Fig. 5b). This is likely to occur mainly in central and western Europe (Fig. 3) and results in a remarkable mean increase in the level of invasion by 2080 (Fig. 5a).

Under the SEDG scenario (Fig. 4), both the projected increase and decrease in the mean level of invasion were the smallest (Fig. 5b). Generally the regions showing an increase and decrease were roughly the same as under the GRAS or BAMBU scenarios. Because of the small decreases in the levels of invasion, the SEDG scenario resulted in projections of significantly larger mean levels of invasion across Europe than the GRAS scenario.

DISCUSSION

In this study, we first mapped the current levels of invasion for the baseline land-use data, which corresponded to year 2000, and then we projected levels of invasion on the land-use scenarios for three target years: 2020, 2050 and 2080. Because of increased uncertainty towards the future (Rounsevell *et al.*, 2006), it was necessary to use coarser spatial resolution and coarser habitat classification than in the previous study that mapped current level of plant invasions in Europe (Chytrý *et al.*, 2009a). However, a considerable similarity between the current baseline map (Fig. 1) and the more detailed map of the previous study indicated that the current input data were reliable.

At a coarse European scale, distribution of land-use categories is driven by climate (Thuiller *et al.*, 2004), but at finer scales, it is driven by socio-economic processes. Species invasions are driven by both climate (Walther *et al.*, 2009) and land-use, but the effect of climate on the level of invasion of particular sites is much weaker than the effect of land-use or habitats (Chytrý *et al.*, 2008a). The land-use scenarios used in this study involved projections of future climate change (Bondeau *et al.*, 2007), assuming that socio-economic processes cause climate change, but they are themselves changed in response to the climate change. Land-use changes thus depend on both socio-economy and climate, while plant invasions depend on all of these three factors, being most closely linked to land-use change.

Under all the three scenarios of the future socio-economic development examined in this study, the magnitude and pattern of the level of plant invasion within European regions is projected to change in the 21st century (Figs. 2–4). Scenarios show that in north-western and northern Europe the levels of invasion may increase more than elsewhere, mainly due spread of alien plants to the landscapes with biofuel crop plantations established in the places of former grasslands (Tuck *et al*., 2006; Reginster & Rounsevell, this issue). In contrast, some areas such as eastern Europe and some parts of southern Europe may experience no increase, or even decrease, in the level of invasion. To a large extent, these projected changes in the level of invasion are due to the abandonment of arable land (Reginster & Rounsevell, this issue), because agricultural areas are particularly suitable for the spread of many alien species (Pyšek *et al*., 2005; Chytrý *et al*., 2008a, b).

Perhaps a surprising result of this study is that the largest overall decrease in the level of invasion is projected under the GRAS scenario (Fig. 5). This scenario, assuming economic deregulation and globalization (Spangenberg *et al.*, this issue), supposes that in the first half of the 21st century large areas of agricultural land will be abandoned especially in eastern Europe and also in some coastal areas and some regions of southern Europe, most notably south-western France. In the second half of this century further abandonment is projected also in central and western Europe (Reginster & Rounsevell, this issue). Succession on abandoned fields may result in a decreased level of invasion across the landscapes, because the proportion of alien plant species is known to decrease during secondary succession due to the establishment of competitively strong native species in the mid and late successional stages (Rejmánek, 1989; Pino *et al.*, 2006). In contrast, the establishment of biofuel plantations in places of former grasslands, as expected under the GRAS scenario especially for north-western Europe, may result in increased levels of plant invasion there. Thus this scenario results in a strong geographical polarization between the areas with considerable increase of plant invasions and the areas where invasions can be less important than today (Fig. 2). However, areas with projected decrease in the level of invasion are not likely to experience a parallel decrease in the distribution and impact of serious invaders that they already harbour. Established serious invaders (those with strong negative impacts on economy or biodiversity) are difficult to eradicate and unlikely to retreat due to changing land-use without human intervention (Rejmánek & Pitcairn, 2002). As serious invaders are likely to arrive in ‘increase’ areas but not disappear from ‘decrease’ areas, invasions under the GRAS scenario may have more serious consequences than it appears just on the basis of levels of invasion.

The SEDG scenario (Fig. 4), which supposes sustainable development with high priority of environmental issues and support for extensive agriculture even in areas where it is less profitable (Spangenberg *et al.*, this issue), leads to higher overall levels of invasion in Europe. Under this scenario, the decrease in the level of invasion is very small and although the increase is smaller than under the GRAS or BAMBU scenarios, it results in a significantly larger net overall increase across Europe than under GRAS (Fig. 5). It should be noted that the current projections do not account for the increasing level of invasion within habitats, which is very likely to occur, given that more than six alien species capable of naturalization arrive currently in Europe every year (Lambdon *et al.,* 2008; DAISIE, 2009). Thus the actual increase is likely to be even larger than projected here. Polarization between north-western and eastern Europe does occur under SEDG, but it is much less pronounced than under the GRAS or BAMBU scenarios.

The levels of invasion under the BAMBU scenario (Fig. 3), supposing implementation of current regulation policies, are similar to SEDG. However, due to an intermediate decrease in the level of invasion in some areas, coupled with large increases in other areas, this scenario results in the highest overall level of invasion across Europe by 2080 (Fig. 5a). Thus, if the regulation-oriented policy decisions already made, but not yet fully implemented, are implemented and enforced, the problem of invasive plant species may increase in importance especially in countries of north-western Europe, which are already now most affected by invasions. For example, the United Kingdom and Belgium have the highest densities of naturalized neophytes of all European countries (Lambdon *et al*., 2008). The risk of future invasions is highest in the British Isles, and Ireland in particular.

The measure used here to quantify future invasions is based on all alien species rather than invasive pest species which are of interest to environmental managers. However, the strong positive relationship for the 2000 baseline data between the mean level of invasion in grid cells and the percentage of the total number of the plant species that are included among the 100 worst invaders in Europe (DAISIE, 2009) clearly illustrates that high level of invasion also means an increased probability of the occurrence of invasive pest species (Rejmánek & Randall, 2004). Areas for which high levels of invasion are projected are thus likely to receive not only more alien species, but also more invasive species that cause environmental or economic damage (Vilà *et al*., 2009).

CONCLUSIONS

The three scenarios considered in this study provide internally consistent illustrations of plausible and possible futures. However, their probability cannot be quantified and their realization depends on whether or not their assumptions will be realized. Deviations from the linear development trajectories of these scenarios are possible (shock events: Spangenberg *et al.*, this issue). Nevertheless, these scenarios provide valuable insights into the relationships between possible future orientations of European policy and plant invasions.

An important lesson learned from this study is that none of the currently dominating policy options in itself will be able to stop or reduce the ongoing process of plant invasions, although minor reductions are possible in some regions. This conclusion is also valid for policies favouring sustainable development and environmental protection (SEDG scenario), which may even result in an increase in the rate of spread of alien plants in some regions by supporting agriculture and associated invasion-prone land use in less productive areas. Therefore, invasions require specific policy approaches beyond the general ones, which are currently on the policy agenda. A proactive development and implementation of effective strategies for prevention, eradication and control of invasive alien plants across Europe (Hulme, 2006; Hulme *et al.*, 2009a, b) continue to be of crucial importance, regardless of the future economic development.

ACKNOWLEDGEMENTS

We appreciate the assistance of Xavier Font and Simon Smart with the preparation of vegetation-plot data. This work was supported by the European Union's FP6 Integrated Project ALARM (GOCE-CT-2003-506675; Settele *et al.*, 2005). MC was further funded by the Ministry of Education of the Czech Republic (MSM0021622416), JW, PP and VJ by the Ministry of Education of the Czech Republic (MSM0021620828 and LC06073) and Academy of Sciences of the Czech Republic (AV0Z60050516), and JP and MV by the Spanish Ministry of Science and Innovation (CONSOLIDER-INGENIO CSD2008-00040 "MONTES" and CGL2009-07515).

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Supplementary Material

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Cross-tabulation of the EUNIS habitat types and the MOLUSC land-use categories used for projecting the level of invasion in different European biogeographical regions.

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BIOSKETCH

The authors were members of a consortium studying large-scale environmental risks in Europe within the 6 EU Framework Programme projects ALARM (Assessing Large-Scale Environmental Risks with Tested Methods; 2004–2009). One of the focuses of this project (www.alarmproject.net) was continental patterns of biological invasions and interactions of alien species with other drivers threatening biodiversity. M.C., P.P., I.K. and J.S. conceived the study, M.C., P.P., J.P., L.C.M., M.V. and J.P. analysed the floristic data, J.H.S. developed the socio-economic scenarios, N.D. and I.R. prepared the land-use scenarios, J.W. did the GIS analyses, V.J. computed statistical analyses, M.C. wrote the paper and all authors interpreted the results and commented on the manuscript.

Table 1. Mean percentage levels of invasion by alien plants of different land-use categories in five biogeographical regions of Europe. The level of invasion is defined as the percentage number of species that are aliens (neophytes) in vegetation plots.

Land-use category	British Isles	Atlantic[1]	Boreal	Continental	Mediterranean
Forest	7.8	1.8	0.9	0.9	0.1
Grassland	1.3	1.5	1.7	1.4	1.2
Urban	5.4	5.0	5.0	4.8	4.8
Arable land[2]	13.0	8.6	8.7	5.1	2.8 / 14.2[3]
Abandoned	4.9	3.0	2.8	2.6	2.4

[1]Atlantic region on the European mainland, excluding British Isles. [2]Arable land includes permanent crops and biofuel plantations. [3]The first value refers to non-irrigated and the second to irrigated arable land, because irrigation strongly affects the level of invasion in the Mediterranean areas.

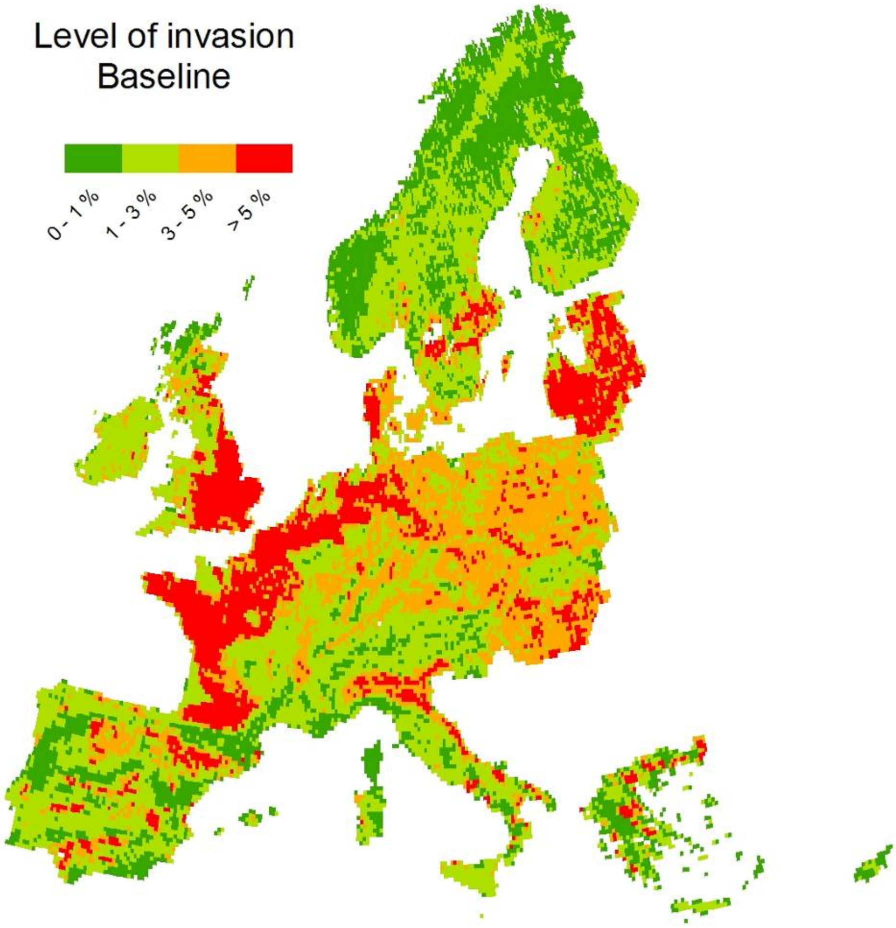

Figure 1 Baseline map showing the level of invasion by alien plants in the year 2000. Average percentages of plant species that are alien (neophytes) in the plots (= level of invasion) were mapped for grid cells of 10’ × 10’.

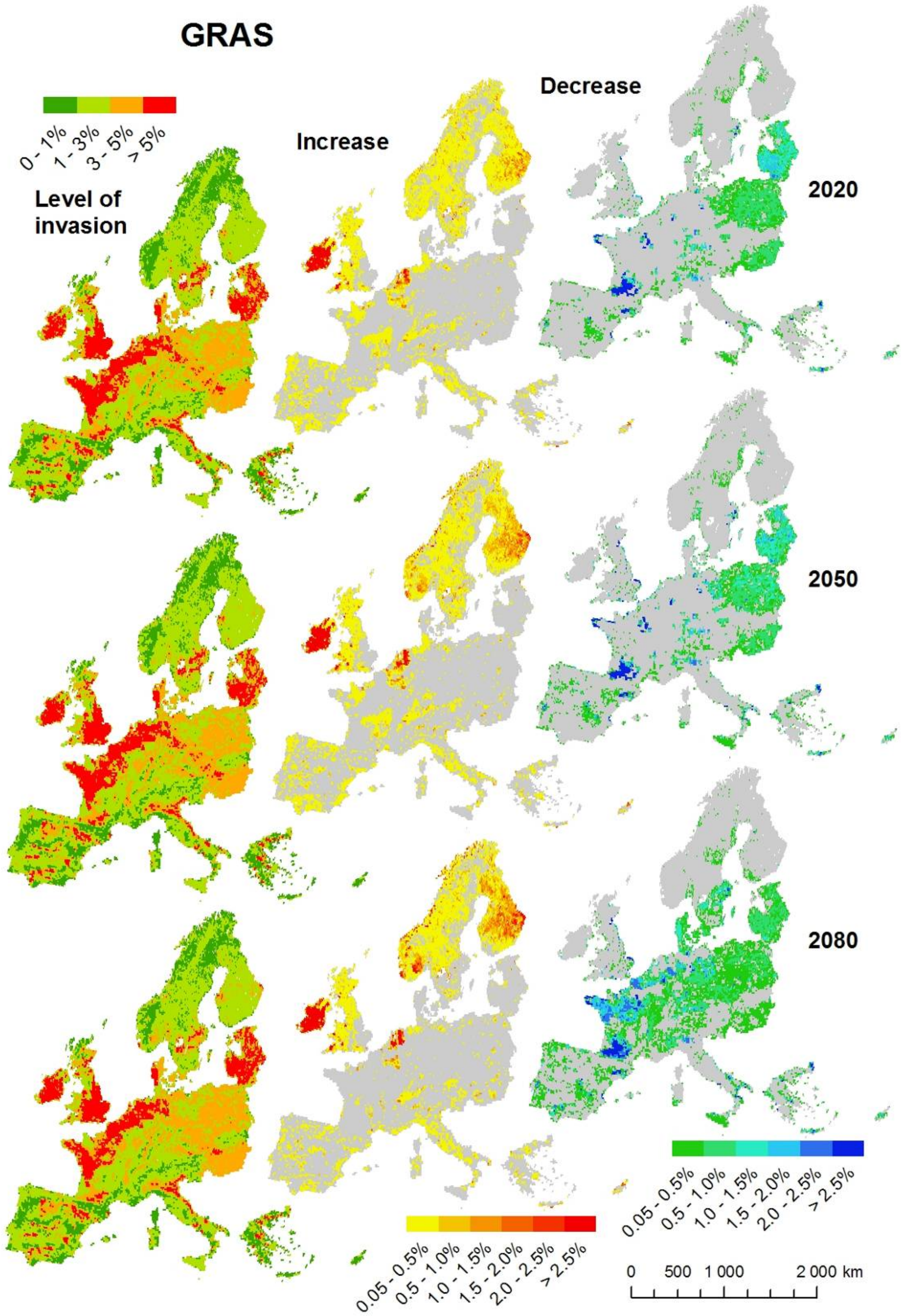

Figure 2 Projected levels of plant invasion in 2020, 2050 and 2080 for the GRAS scenario (oriented on economic development and deregulation). Levels of invasion (left column) are percentages of vascular plant species that are aliens (neophytes) occurring in small areas. Increases and decreases are presented as positive or negative percentage changes in the level of invasion shown in the 2000 baseline map (Fig. 1).

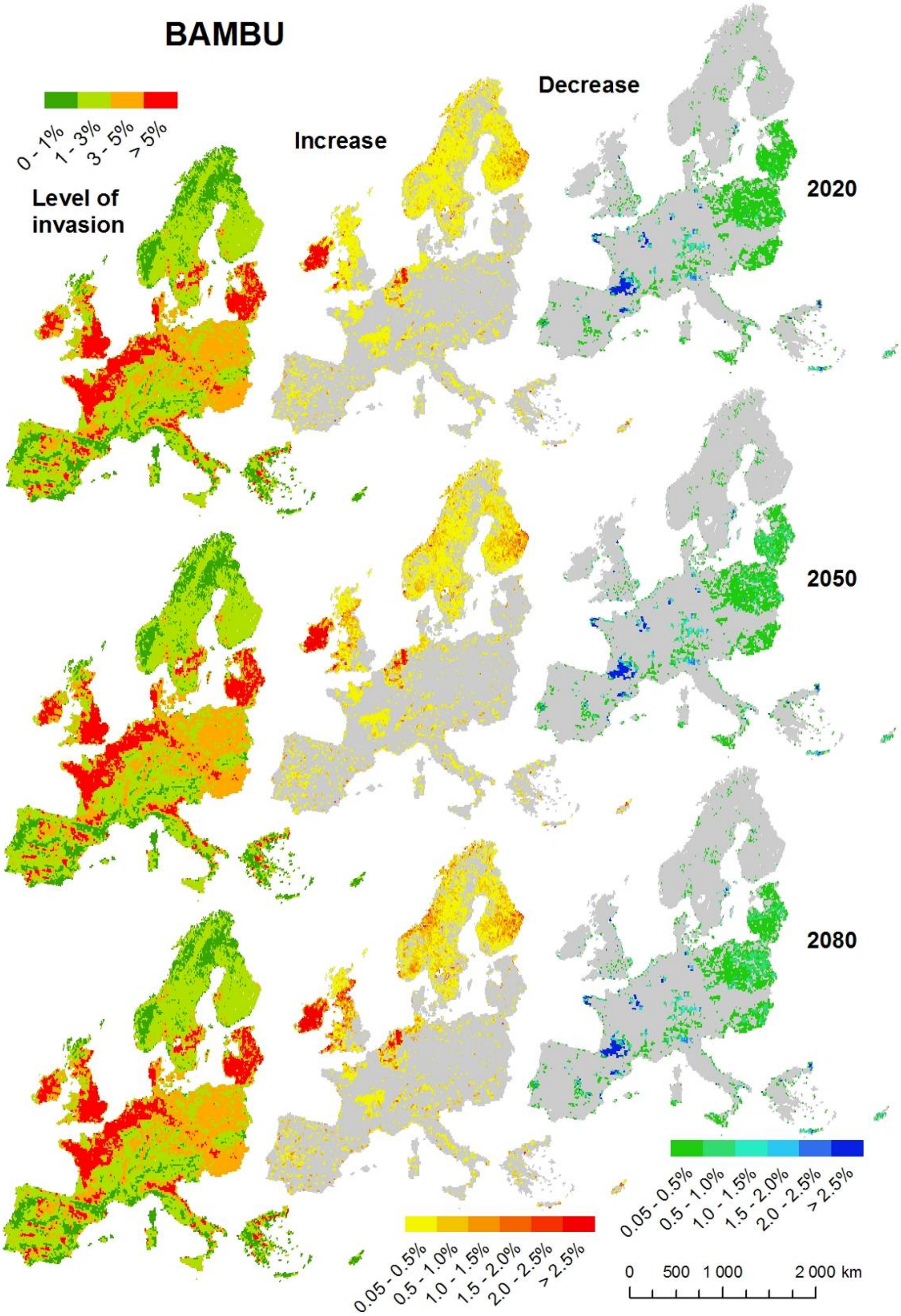

Figure 3 Projected levels of plant invasion in 2020, 2050 and 2080 for the BAMBU scenario (assuming implementation and enforcement of current policy decisions). See Fig. 2 for details.

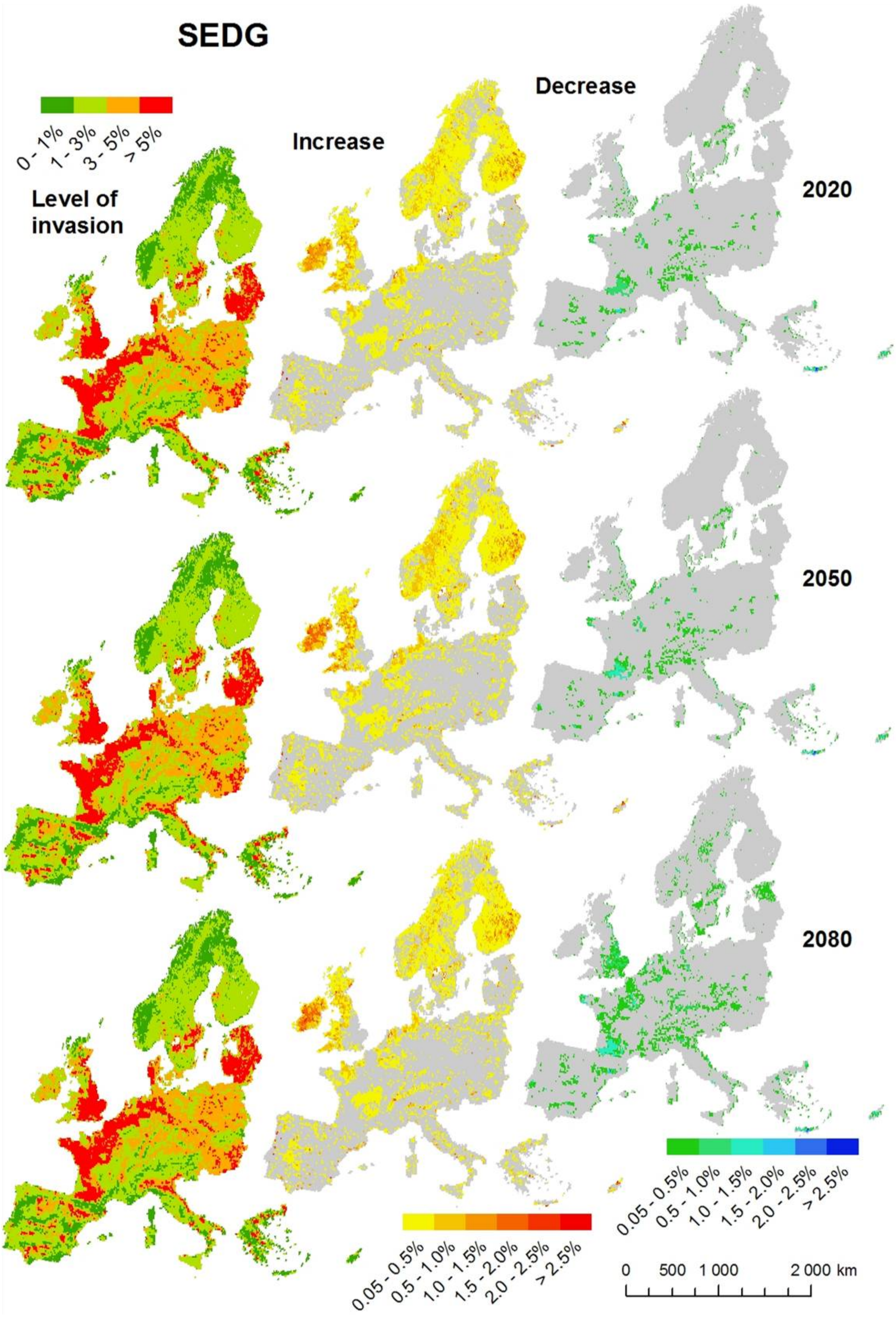

Figure 4 Projected levels of plant invasion in 2020, 2050 and 2080 for the SEDG scenario (oriented on sustainable development). See Fig. 2 for details.

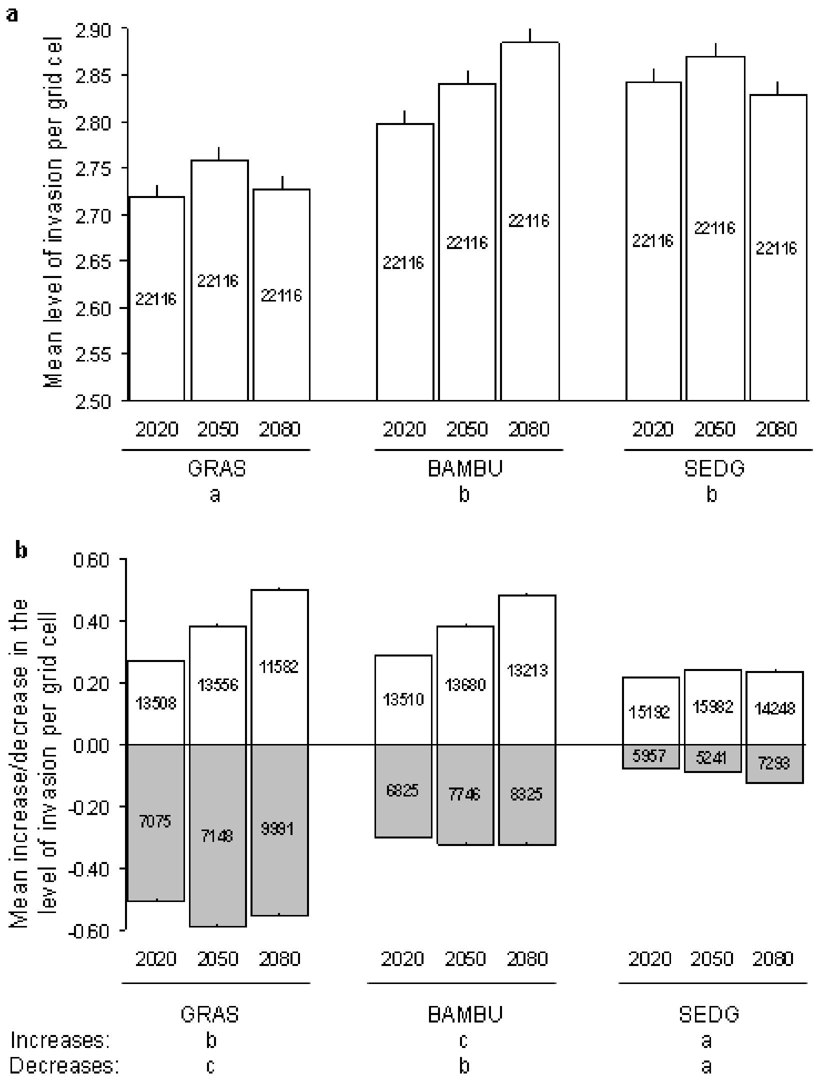

Figure 5 Projected overall changes in the level of invasion by alien plants of all the grid cells in Europe by 2020, 2050 and 2080, under each of three ALARM scenarios. a – mean levels of invasion (= number of alien species/number of all species, %) per grid cell. b – mean positive (increases) or negative (decreases) changes in the levels of invasion per grid cell relative to the 2000 baseline. Vertical lines show standard errors, figures inside the bars are numbers of grid cells. Least square differences (LSD tests; $P < 0.05$) between projected changes for individual scenarios are indicated by small letters below the scenario acronyms: identical letters indicate no differences.

Appendix S1 Cross-tabulation of the EUNIS habitat types and the MOLUSC land-use categories used for projecting the level of invasion in different European biogeographical regions. Values are percentage contributions of habitat types to each land-use category; they were estimated based on Chytrý *et al.* (2009a), Bossard *et al*. (2000), proportion of CORINE land-cover types in particular bioregions, and corrected by expert judgement. Habitat types and their delimitations follow Chytrý *et al*. (2008b, 2009a). Only those EUNIS habitat types that contribute to at least one of the five MOLUSC land-use categories are shown.

Region	Land-use category	A2.5&D6&E6 Saline habitats	E1 Dry grassland	E2 Mesic grassland	E3&E5.4 Wet grasslands	E4 Alpine and subalpine grasslands	E5.1 Anthropogenic herb stands	E5.2 Thermophile woodland fringes	E5.3 Pteridium aquilinum fields	E5.5 Subalpine moist or wet tall-herb and fern stands	F2 Arctic, alpine and subalpine scrub	F3 Temperate scrub	F4 Temperate shrub heathland	F5 Maquis	F6 Garrigue	F7 Spiny mediterranean heaths	FA Hedgerows	G2 Broad-leaved evergreen woodland	G3 Coniferous woodland	G1&4 Broadleaved deciduous and mixed woodland	G5 Disturbed woodland	H5.6 Trampled areas	I1-1 Irrigated arable land, woody crops and gardens	I1-2 Non-irrigated arable land (herbaceous crops)
British Isles	Forest											6					4		20	61	9			
Atlantic	Forest											3					2		20	70	5			
Boreal	Forest											4					2		73	13	8			
Continental	Forest											2							40	53	5			
Mediterranean	Forest											1		10	4			30	15	32	8			
British Isles	Grassland	1	14	47	24	1			4	1		1	4								1			2
Atlantic	Grassland	1	14	46	22				4			1	4								2			6
Boreal	Grassland	1	14	35	19	4			2	3	1	1	6								6			8
Continental	Grassland	1	19	39	21	1		1	1	1		3	1								3			9
Mediterranean	Grassland	2	43	10	7	2		2				1		3	13	1					5		3	8
British Isles	Urban		6	15	1		32														9	23		14
Atlantic	Urban		6	15	1		32														9	23		14
Boreal	Urban		6	15	1		32														9	23		14
Continental	Urban		10	11			32														9	23		15
Mediterranean	Urban		19	2			36														9	23	8	3
British Isles	Arable		1	3	1							2	3								1			89
Atlantic	Arable		1	5	3							2	3								2			84
Boreal	Arable		1	4	3							2	2								2			86
Continental	Arable		2	3	2							2									2		2	87
Mediterranean	Arable non-irrigated		5	3	2									4	5	1								80
Mediterranean	Arable irrigated		1	2	2									2	3								90	
British Isles	Abandoned		5	10	5		15		10			15							5	15	10			10
Atlantic	Abandoned		5	15	5		15		5			15							5	15	10			10
Boreal	Abandoned		5	15	10		15		5			10							15	5	10			10
Continental	Abandoned		10	15	5		15					15							5	15	10			10
Mediterranean	Abandoned		15	5	5		35								15				5		10			10