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Scientific modeling and translanguaging: A multilingual and multimodal approach to support science learning and engagement

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Abstract

Research suggests that translanguaging can be transformative for teaching and learning by making students' diverse linguistic resources a meaningful part of classroom discourse. Building on this study, researchers have explored how translanguaging practices can support learning in STEM (science, technology, engineering, and mathematics), primarily in the context of bilingual classrooms. However, in the United States, most students learn in English-dominant classrooms. In response, researchers and educators have begun to explore strategies for inviting and leveraging translanguaging in English-dominant classrooms, primarily focusing on literacy learning. Less is known about supporting translanguaging in English-dominant STEM classrooms, particularly with monolingual teachers. In an English-dominant sixth-grade STEM classroom engaging in a 9-week ecology unit, we explored how scientific modeling could not only provide a context for inviting translanguaging, but how it could also provide a setting where modeling and translanguaging could be experienced as analogous meaning-making practices. Our findings demonstrate that translanguaging has the potential to support new kinds of learning in English-dominant STEM classrooms, not only about STEM content and practices but also about what counts as legitimate and valuable participation in these spaces.

KEYWORDS
scientific modeling, translanguaging

Douglas B. Clark and Corey E. Brady contributed equally to each other.

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1 | INTRODUCTION

In bilingual classrooms across content areas, research suggests that *translanguaging* can be transformative for teaching and learning by making students' diverse linguistic resources a meaningful part of classroom discourse. Translanguaging theory describes the ways that individuals, including "monolingual" individuals[1], flexibly and fluidly use multiple modes (meaning-making resources, such as image, writing, speech, and action) for reasoning and expression (Blackledge & Creese, 2017; García & Li, 2014; Li, 2018). In contrast to pedagogies of *translation*, which promote "intercultural communication with language that is 'appropriate' for the other group," translanguaging "empower[s] bilingual children so they use their unitary semiotic repertoire to make meaning for themselves" (García et al., 2014, p. 86). In this way, translanguaging has the potential to support new kinds of learning, not only about language and content but also about what counts as legitimate and valuable participation in institutional spaces, like schools (García et al., 2017; Makoni & Pennycook, 2007; Otheguy et al., 2015).

Research about translanguaging originated in bilingual classrooms in which students shared linguistic resources (e.g., students identified as speakers of English and Welsh; Williams, 1994). Foundational studies about translanguaging primarily aimed to understand students' ways of being, interacting, and learning in such spaces (Baker, 2011; García, 2009; Lewis et al., 2012; Williams, 1994). Building on this study, researchers have explored how translanguaging practices can support learning in STEM (science, technology, engineering, and mathematics), again in the context of bilingual classrooms (Karlsson et al., 2019; Oliveira et al., 2019; Poza, 2018; Probyn, 2015). A number of these studies have explored how translanguaging practices can support specific scientific practices, most often focusing on argumentation (Infante & Licona, 2018; Licona & Kelly, 2019; Reigh & Miller, 2020; Wu et al., 2019).

However, in the United States, most students learn in English-dominant classrooms (Shin, 2017). Inviting translanguaging in English-dominant classrooms is challenging, in part because ideologies prevalent in US schools valorize opposing themes: "Transparent communication and emancipation through a collective standard variety [English] on the one hand, and respect for individual difference, freedom of expression and equality (of languages, among other things) on the other" (Jaspers, 2018, p. 6). In response, additive approaches to bilingualism often advocate helping students engage in "academic" forms of discourse in classroom contexts while valuing language diversity in other contexts (Flores & Rosa, 2015). Following these ideologies, students in English-dominant classrooms are rarely invited to use languages other than English for STEM learning. Even when students are invited to leverage their full linguistic repertoires, they often resist invitations to translanguage because these practices can be perceived as socially risky (Charalambous et al., 2016; Cole et al., 2016; Daniel et al., 2019).

In response to these challenges, researchers and educators have begun to explore strategies for inviting and leveraging translanguaging in English-dominant classrooms. To date, this study has primarily focused on literacy learning. Most studies have taken place in elementary classrooms and focus on students' linguistic resources (Daniel et al., 2019; Machado & Hartman, 2019; Ranker, 2009; L. W. Rowe, 2020; Zapata & Laman, 2016), although some studies have taken place in secondary classrooms and focus on students' multimodal resources for meaning-making and expression (see Smith et al., 2020 for a review of research about multimodal composition in both dual-language and English-centric secondary classrooms). Together, these studies have identified several promising strategies for supporting multilingual and multimodal composing, including: Explicitly valuing students' language and cultures (García & Kleifgen, 2019; L. W. Rowe, 2018), modeling multilingual composing (Machado & Hartman, 2019), introducing multilingual mentor texts (Zapata & Laman, 2016), leveraging digital tools to mediate heritage-language use (D. W> Rowe & Miller, 2016; L. W. Rowe, 2020; Vogel et al., 2018), and emphasizing disciplinary reasons for translanguaging (Canagarajah, 2013; García & Kleyn, 2016).

Still, less is known about supporting translanguaging in English-dominant STEM classrooms, particularly with monolingual teachers. As described above, research suggests that certain scientific practices, like argumentation, may be well-suited to supporting translanguaging in STEM. In this paper, we focus on another practice, scientific modeling: the practice of creating, using, or revising models (conceptual or material representations) to reason or

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express ideas about a referent phenomenon (e.g., Latour, 1999; National Research Council, 2012; Nersessian, 2008). Like translanguaging, scientific modeling relies on the use of multimodal representations for meaning-making and expression. Thus, we explored how scientific modeling could not only provide a context for inviting translanguaging, but how it could also provide a setting where modeling and translanguaging could be experienced as analogous meaning-making practices. In an English-dominant classroom, we aimed to understand how we might begin to leverage the transformative potential of translanguaging during scientific modeling to support learning and engagement for “bilingual” students who identified as speakers of multiple languages and “monolingual” students who identified as speakers of English.

2 | THEORETICAL FRAMEWORK

First, we provide an overview of translanguaging theory and pedagogy, focusing on STEM classrooms and English-dominant classrooms. Then, we explore connections between translanguaging and theories of social semiotics that emphasize nonlinguistic modes, and we consider multimodality from the perspectives of translanguaging and disciplinary science. Building on this study, we present conjectures about how connecting translanguaging and modeling could shape learning and engagement in English-dominant classrooms.

2.1 | Translanguaging: Theory and pedagogy

Historically, bilingual education has defined “named” languages (e.g., English and Spanish) as bounded, autonomous systems (Turner & Lin, 2020). More recently, researchers have argued that these perspectives do not reflect how language operates in the world. Focusing only on the symbolic property of language overlooks how language shapes identities and experiences (Ochs, 2012). Moreover, characterizing named languages as separate and stable produces limiting views that have real and material consequences for minoritized communities (Makoni & Pennycook, 2007; Milroy, 2001). For instance, in the United States, nationalistic language ideologies have privileged “standard” varieties of English—varieties of English that are not objectively correct but are perceived to be neutral and are not overtly stigmatized (Lippi-Green, 2011). Valuing “standard” English positions the use of minoritized language varieties as different or deficient (Bucholtz & Hall, 2005; Flores & Rosa, 2015; García-Sánchez et al., 2016; Heller & McElhinny, 2017; Ricento, 2013). Such ideologies can constrain multilingual discourse (Makalela, 2015), endanger language diversity (Perez et al., 2016), and lead to academic disparities (Gallo et al., 2014; Lee & McCarty, 2015).

In contrast, translanguaging theory builds from the language practices of bilingual communities, describing how individuals make meaning by simultaneously drawing on resources from multiple named languages (García, 2009; Li, 2018) and multiple modes (Hua et al., 2019; Sherris & Adami, 2019). Translanguaging theory aligns with research from linguistics and bilingual education that posits that named languages are politically and socially constructed (Ag & Jørgensen, 2013; Canagarajah, 2013; García & Kleyn, 2016; Makoni & Pennycook, 2007) and characterizes languages as “living”—constantly changing and evolving (Anzaldua, 1987; Goodwin, 2017; Wilson & Kamana, 2009). From this perspective, researchers and educators have called for the creation of complex, multilingual spaces, in which language learning aims toward versatility and agility rather than mastery and control (Hemphill & Blakely, 2019; Hornberger & Link, 2012). Such spaces could include multiple literacies that might not be shared among all members of the community (Canagarajah, 2013; Pennycook & Makoni, 2020).

Even so, research about translanguaging has primarily focused on bilingual classrooms in which students share linguistic resources. In such contexts, bilingual students are supported to mobilize their full linguistic repertoire as a resource for learning and to extend that repertoire as they develop new understandings about content and about language (García et al., 2017). Ultimately, translanguaging is intended to be transformative of learning by

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disrupting socially constructed language hierarchies and restrictive language policies (e.g., English-only policies in US schools) that have contributed to the oppression of minoritized students (Otheguy et al., 2015). Research demonstrates that pedagogies of translanguaging can support students' development of literacy resources and deepen students' understanding of texts (e.g., García & Kleifgen, 2019). Moreover, introducing translanguaging pedagogies to teachers can initiate ideological shifts, resulting in changes to schools' language policies (Menken & Sánchez, 2019; Viesca & Teemant, 2019). Still, conflicting ideologies can exist in translanguaging classrooms. Martínez et al. (2015) describe dual-language classrooms that promote bilingualism and fluidly integrate Spanish and English, yet at times echo ideologies of language separation. For example, in one classroom, although students were encouraged to speak using their full formal and informal linguistic repertoire, they were asked to use either "academic" Spanish or "academic" English during reading and writing activities. This study emphasizes the importance of not only encouraging translanguaging, but engaging schools, teachers, and students in critical conversations about language use and meaning-making practices in classrooms (Li, 2018).

In STEM classrooms specifically, research shows that translanguaging can promote language development, high-order thinking, and conceptual understanding (Domínguez, 2011; Espinosa & Herrera, 2016; Esquinca et al., 2014; Moschkovich, 2015; Oliveira et al., 2019; Poza, 2018; Razfar, 2013), contributing to more equitable learning environments for bilingual students (Hudicourt-Barnes, 2003; Karlsson et al., 2019; Lin & Wu, 2015; Probyn, 2015; Williams, 2020). Recently, a number of studies have focused on connecting translanguaging practices and the scientific practice of argumentation (Infante & Licona, 2018; Reigh & Miller, 2020; Wu et al., 2019). For example, Licona and Kelly (2019) show how drawing on a classroom's full linguistic repertoire can help students understand nuanced epistemic dimensions of argumentation, such as the function of a claim or the role of reasoning in an argument. They suggest that linking translanguaging and language-intensive practices such as argumentation can be particularly fruitful for the inclusion of students classified as English learners (ELs) in science classrooms, because translanguaging practices increase students' access to linguistic resources for meaning-making. However, as Reigh and Miller (2020) have pointed out, beyond argumentation, relatively less is known about connecting translanguaging with specific science practices.

Though most translanguaging studies occur in bilingual classrooms, researchers have begun to explore how to support translanguaging in English-dominant classrooms. Even in classrooms without explicit English-only policies, students are often hesitant to use and share languages other than English. To facilitate fluid discourse with English-speaking teachers or peers, emergent bilingual students more often leverage English-language resources along with nonlinguistic resources (Williams, 2020). Students can be reluctant to use languages other than English in school for a number of reasons: because they do not see languages other than English as part of the "academic" language valued in school, because they are concerned about distancing themselves from monolingual peers, or because they are concerned about taking on a "problematic" identity (Charalambous et al., 2016; Cole et al., 2016; Perez et al., 2016).

In response to these challenges, researchers have identified supports for translanguaging in English-dominant classrooms. This study has primarily focused on literacy learning, and most studies have taken place in elementary classrooms and focus on students' linguistic resources (Daniel et al., 2019; Machado & Hartman, 2019; Ranker, 2009; L. W. Rowe, 2020; Zapata & Laman, 2016). These studies have identified several promising strategies for supporting multilingual and multimodal composing. They emphasize the importance of building a community that is inclusive of all students' languages and cultures (García & Kleyn, 2016) by showing interest in students' heritage languages, modeling learning new languages from students, and facilitating discussions about languages and cultures (L. W. Rowe, 2018). This approach can involve helping students develop critical understandings of language ideologies that separate and standardize languages, disrupting established monolingual and monoglossic understandings (García & Kleyn, 2016; Li, 2018; Seltzer & de los Ríos, 2018).

Strategies that invite and leverage multiple languages include modeling multilingual composing (Machado & Hartman, 2019), introducing multilingual mentor texts (Seltzer, 2020; Zapata & Laman, 2016), and leveraging digital tools, including multimodal eBooks and machine translation tools like Google Translate, to mediate

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heritage-language use (D. W. Rowe & Miller, 2016; L. W. Rowe, 2020; Vogel et al., 2018). In addition, researchers have found that emphasizing disciplinary reasons for translanguaging can support multilingual and multimodal composing (Canagarajah, 2013; Durán, 2016; García & Kleyn, 2016; L. W. Rowe, 2018). In the context of literacy, researchers and educators have encouraged multilingual composing by leveraging a number of disciplinary reasons for translanguaging, including: speaking to a bilingual audience (Durán, 2016; 2017; D. W. Rowe & Miller, 2016), authentically representing the voice of the author, the characters, or the setting of a text (Canagarajah, 2013; Rowe, 2018); teaching languages to others (L. W. Rowe, 2018), identifying and analyzing translanguaging as a literary device (García & Kleyn, 2016), and supporting deeper understandings of texts (García & Kleifgen, 2019).

Yet, to date, few studies have explored how disciplinary reasons can be leveraged to support multilingual and multimodal practices in STEM classrooms. In this paper, we aim to build on research about supporting translanguaging in classrooms to consider how translanguaging might shape students' opportunities for learning and engagement in an English-dominant STEM classroom. Specifically, we focus on how scientific modeling, a multimodal STEM practice, might be framed as a disciplinary reason for translanguaging in STEM.

2.2 | Multimodality in translanguaging and scientific modeling

Although most closely associated with *linguistic* repertoires, translanguaging practices also include multimodal *semiotic* repertoires (Blackledge & Creese, 2017; Hua et al., 2019; Li, 2018; Sherris & Adami, 2019). Historically, nonlinguistic modes (e.g., drawing, gesture, action) have typically been viewed in bilingual education as compensatory to language (Grapin, 2019). Instead, translanguaging positions all modes as valuable for meaning-making and expression (Otheguy et al., 2015). Theories of social semiotics describe each mode as having unique affordances and commitments (Bezemer & Kress, 2008; Goodwin, 2017; Lemke, 2000; Ranker, 2009). For instance, visual modes afford and demand representations of spatial relations between objects, such as proximity and adjacency, whereas representing spatial relationships is optional in written modes. In contrast, written modes have a stronger commitment to sequence, even when the referent phenomenon is nonsequential, because texts are read linearly. By inviting students' full semiotic repertoires for classroom learning, translanguaging pedagogies have the potential to help students recognize and leverage the affordances of a wider range of semiotic resources for meaning-making and expression (Hawkins, 2018; Sherris & Adami, 2019).

Although most studies about translanguaging in US classrooms focus on linguistic modes, some have emphasized the importance of multimodality (Radke et al., 2020; Smith et al., 2017). For instance, in an English Language Arts classroom, Pacheco, Smith, and colleagues (Pacheco & Smith, 2015; Smith et al., 2017) integrated theories of translanguaging and social semiotics to understand students' multilingual and multimodal composing processes as they created presentations about a personal hero. They found that multimodal composing was generative for students, who iteratively used different modes (talk, text, and visuals) to compose their projects. Moreover, multimodal composing mediated content learning; students conducted interviews and research using English and other languages, and they explored themes of heroism with text, talk, and images. In the process, students described becoming increasingly comfortable with using and sharing their heritage languages in this classroom.

Though not explicitly focusing on translanguaging theory, substantial research demonstrates the promise of multimodality for supporting learning for emergent bilingual students across grade levels, contexts, and content areas. Smith et al. (2020) reviewed 70 studies focused on emergent bilingual students and multimodal composing in secondary classrooms. These studies show that emphasizing multimodality can help students explore their identities and agentively represent themselves, reshape classroom spaces by challenging ideologies about language and literacy, and support students' learning about design, language, and content. In science classrooms specifically, multimodal composing has been shown to mediate content learning for emergent bilingual students by bringing into contact multiple literacies (e.g., print literacies, as well as environmental, scientific, spiritual, cultural, and digital literacies; Goulah, 2017) and by helping students engage in disciplinary practices for meaning-making

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(e.g., data visualization; Zheng et al., 2014) and expression, (e.g., modeling; Grapin, 2019). Multimodal resources can support science discourse as well; Williams (2020) illustrates how emergent bilingual students in a fifth-grade science classroom used multiple modes (e.g., gesture, tactile, imitation, and pantomime) for several purposes: Developing and expressing ideas, mediating language, and supporting the flow of discourse.

In STEM classrooms, researchers are beginning to explore designs for STEM learning informed explicitly by translanguaging theory (Radke et al., 2020; Vogel et al., 2019). For instance, Radke et al. (2020) describe students using a multilingual and multimodal programming environment to make sense of the effects of Hurricane María on Puerto Rico. The students leveraged their full semiotic, cultural, and experiential repertoires to quantitively explore statistical modeling and qualitatively explore human stories of migration. This study explicitly draws on translanguaging theory, and it contributes to a substantial body of research about STEM disciplines and STEM education that emphasizes the importance of multimodality.

In science, multimodality generatively shapes the ways that scientists see and understand phenomena (Farris et al., 2020; Gouvea & Passmore, 2017; Latour, 1999; Lemke, 2000; MacLeod & Nersessian, 2013; Nersessian, 2017). In particular, the scientific practice of modeling relies heavily on multimodality. Modeling involves coordinating multiple representations that offer unique perspectives to build increasingly nuanced understandings of complex phenomena. For example, Gooding (2006) illustrates how Faraday used several representations to explain why aquatic microorganisms seemed to have biologically implausible wheels propelling them through water. Faraday observed that the linear spokes of wheels appear curved when moving quickly. To test this analogy, he created physical simulators that reproduced the illusion of rotors. With sketches and physical models, he explained that what appeared to be rotors were in fact rapidly moving but anchored *ciliae*. Each model offered unique affordances because each was shaped by different modal resources. Static sketches allowed Faraday to consider in detail the structural components of microorganisms and spinning wheels. Dynamic physical structures and simulations allowed Faraday to test and refine his explanation as he attempted to reproduce the optical illusion of rotors. In this way, Faraday used hybrid resources to compare and combine features of phenomena at a perceptual and conceptual level.

Engaging with multiple models supports learning in part because different representations have specific affordances for learning (Ainsworth & Prain, 2020; Lehrer, 2009; Parnafes & diSessa, 2004; Pierson et al., 2017). For example, diagrammatic models leverage students' understanding of resemblance while facilitating abstraction and reduction as students attempt to represent complex phenomena two-dimensionally (Lehrer & Schauble, 2015; Manz, 2012). Physical models allow students to grapple with the material challenges of designing measures and interpreting data, providing students with opportunities to evaluate the fit between their models and the world (Lehrer, 2009; Manz, 2012; Penner et al., 1998). Computational models represent phenomena virtually, which can enable students to explore phenomena at scales that would not otherwise be observable in a classroom (Sengupta & Wilensky, 2009). Embodied models can provide resources for understanding complex systems and the logic that underlies computational models (Brady et al., 2016; Klopfer, 2003; Wilensky & Stroup, 1999), and they can serve as a reflective tool that invites and incorporates multimodal resources (Pierson & Brady, 2020). In addition, beyond *using* models, *creating* multimodal models also supports STEM learning by helping students carefully attend to the meaning of representational forms and by creating opportunities for students to critically reflect on the representations they design (diSessa et al., 1991; Enyedy, 2005; Lehrer & Schauble, 2012). In this sense, activities like computer coding that are often framed in a technocentric way (building computational artifacts) can instead be understood as a meaning-making practice of voicing computational utterances (Sengupta et al., 2021).

In summary, emphasizing multimodality shows potential for supporting science learning for students with a wide range of linguistic resources, including students who identify as “monolingual” or “bilingual” as well as students classified as ELs. In this paper, we explore how focusing on scientific modeling and translanguaging practices in an English-dominant STEM classroom create opportunities for students to leverage diverse linguistic and nonlinguistic modes to make sense of phenomena related to biology and ecology.

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2.3 | Designing to support translanguaging and scientific modeling

To connect translanguaging and modeling practices, we draw on K. D. Gutiérrez and Jurow's (2016) *syncretic* approach to design. This approach aims to connect and reorganize everyday and disciplinary practices to create new forms of knowledge and expertise in service of equitable learning, empowering nondominant communities to appropriate and transform disciplinary practices. K. D. Gutiérrez and Jurow (2016) illustrate this approach by describing the Migrant Student Leadership Institute (MSLI), a design intended to support high school students from migrant farmworker backgrounds. The goal of MSLI was to help students develop sociocritical literacies that addressed contradictions and possibilities in everyday practices and institutions of schooling. For example, the project addressed the contradiction between students' "need and right to leverage their full linguistic toolkits in learning" (p. 573) and the English-only language practices in schools. To address this tension, researchers foregrounded goals related to learning and equity by privileging students' linguistic practices, including forms of translanguaging, and by supporting students in developing literacy practices valued in high schools and universities. One aspect of MSLI that supported these goals was the creation of syncretic textual forms, which reorganized everyday genres, including the *testimonio*, a form of historicizing narrative, and school-based genres, such as expository essays and extended definitions. They found that the hybridity of these texts increased the likelihood that they could be valued both in formal settings and by MSLI students and their communities (Gutiérrez & Jurow, 2016; Gutiérrez, 2008).

Other researchers have taken up this syncretic approach to design in a number of contexts, including work that moves outside of literacy to embrace representationally-rich STEM practices (e.g., Barajas-López & Bang, 2018, Suárez et al., 2018). Across these studies, researchers find that a syncretic approach to design offers participants a means to see their everyday practices as valuable in disciplinary contexts while creating opportunities for participants to access and transform disciplinary practices, creating new practices that are meaningful within a specific community. In this study, we aim to explore the creation of classroom practices that blend ideas from translanguaging and scientific modeling to leverage students' multilingual and multimodal resources for meaning-making and expression in STEM.

Specifically, we identify and leverage disciplinary reasons for translanguaging within modeling practices: Leveraging multilingual and multimodal resources during modeling could help students understand complex phenomena and share ideas. We conjecture that leveraging multiple modes and languages could support learning by helping students see phenomena from new perspectives, because meaning shifts across modes (Bezemer & Kress, 2008) and because students' linguistic resources are connected to unique experiences and understandings (Pacheco & Smith, 2015). These shifts in perspective could help students understand complex phenomena (like ecosystems and population dynamics) in increasingly nuanced ways as they compare and select among representations of phenomena. Comparing representations could also help students consider the affordances of representations, a practice valued in both scientific modeling (diSessa et al., 1991; Nersessian, 2017) and literacy (García & Kleyn, 2016; Seltzer & de los Ríos, 2018) that could contribute to students' capacity for expressing ideas. In addition, inviting diverse representations and modes (including linguistic, diagrammatic, physical, embodied, and computational representations) could contribute to shifts in perspectives that might help students attend to ideas (e.g., concerns related to ethics; Pierson et al., 2020b) that might be missing from curricula or standards, shaping not only the way language is used in the classroom, but also creating opportunities for critically examining disciplinary content (Seltzer & de los Ríos, 2018). In this sense, syncretic translanguaging-modeling practices could be transformative of STEM learning in an English-dominant classroom, both for "bilingual" and "monolingual" students.

In this paper, rather than evaluating instructional practices or learning activities as final products, we use our design as a context in which we explore the promise of translanguaging for transforming learning and participation in an English-dominant STEM classroom. We ask:

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1. How can we begin to invite and support translanguaging in an English-dominant STEM classroom?
2. How does emphasizing translanguaging during modeling shape learning and engagement for students, including "bilingual" and "monolingual" students?

3 | METHODS

We explore our research questions within a design study (Cobb et al., 2003; Sandoval, 2014), which involves "engineering particular forms of learning and systematically studying those forms of learning" within the designed context that supports them (Cobb et al., 2003, p. 9). We used conjecture mapping (Sandoval, 2014) and retrospective analysis (Cobb et al., 2003) to specify design features, embody these features in a classroom context, and describe their influence (in this case, how students responded to invitations to use multiple modes and languages during modeling, and how these practices shaped learning and engagement).

3.1 | Research context

The current study was conducted in a public middle school located in a small suburban school district in the southeastern United States in collaboration with a STEM teacher, Ms. S, in her 26th year of teaching. Ms. S and the first author, Ashlyn, co-designed and co-taught all lessons for the unit. Ms. S and Ashlyn are both white, monolingual English speakers, and they were both interested in supporting multilingual and multimodal STEM learning based on their experiences as teachers of linguistically diverse students. Previously, their work together had focused on *multimodal* modeling, but both were interested in better-supporting students' use of *multilingual* resources to create a more equitable environment for learning and participation. In this design iteration, Ashlyn suggested focusing on translanguaging to explicitly challenge the monoglossic norms in the classroom and to legitimize and value multilingual resources.

Ms. S's sixth-grade STEM class participated in the project (20 students). According to the state report card, 18% of the school's students qualify for free or reduced lunch. The students are culturally and linguistically diverse: 55% of students identify as White, 34% as Hispanic or Latino, 7% as Black or African American, and 4% as Asian. In addition, 8% are classified as ELs. In this district, students are selected for EL screening based on a Home Language Survey, and they are classified as ELs based on the idea proficiency test and English language development assessments, which are used with state content assessments to monitor progress annually. On the basis of these assessments, the district determines whether a student's English proficiency "does not enable them to succeed in school." According to the district website, students are typically classified as ELs for 4–7 years. In Ms. S's class, five students were classified as ELs, all of whom identified as bilingual.

In the broader population of students classified as ELs, there is heterogeneity in terms of language background, ethnicity, culture, educational experience, and socioeconomic status. In this classroom, all five of the students classified as ELs spoke English and Spanish (Carlos, Jennifer, Jesús, Luis, and Luna). All five students regularly used English in class, and four of the five (Carlos, Jennifer, Jesús, and Luis) regularly used Spanish during class when speaking to bilingual peers. The students expressed different levels of confidence about writing in English and Spanish. Two of the students (Carlos and Luna) said they did not like writing in either language; Carlos told Ashlyn during class that he did not like writing because he was not good at spelling. The other three students (Jennifer, Jesús, and Luis) wrote in English and Spanish with varying degrees of fluidity; for example, Jennifer wrote in either English or Spanish, whereas Luis combined English and Spanish words within phrases and sentences. In addition to students classified as ELs, another student, Eli, identified as bilingual. Eli spoke Korean with his parents. He shared some Korean terms in whole-class discussions; however, to our knowledge, he did not speak or write using Korean during modeling activities.

This study is part of the larger SAIL + CTM project (NSF DRL#1742138). This iterative design-based study serves as vanguard for the larger project, developing and testing principles that could be applied in the more

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formalized SAIL + CTM curriculum. The pilot implementation of this study took place during the last quarter of 2018 (see Pierson et al., 2020a). The present study analyzes data from the fourth cycle of the design, which occurred during the third quarter of 2019 because this cycle focused specifically on integrating translanguaging and modeling. Lessons for the project took place three times a week during the students' 9-week STEM class for a total of 23 class sessions (56 min each). The unit was designed to support standards from the state and standards from the Next Generation Science Standards (see Table 1).

All iterations of the design foregrounded modeling, a practice that affords students opportunities to reason and express ideas across multimodal tangible and testable representations, facilitating argumentation and explanation (Lehrer & Schauble, 2015). Throughout the unit, students created different types of multimodal models that represented ecosystems, including diagrammatic, physical, computational, and embodied models. These model types were chosen for the broad range of modes they could integrate (including static and dynamic images, text, code, symbols, physical structures, actions, and gestures) as well as the complementary affordances of these model types for learning, as described in the theoretical framework. Although the model types were chosen by Ms. S and Ashlyn, students were allowed to choose the modes and languages they used within each of their models. Thus, the design offered students opportunities to represent meaning across a range of modes.

Across all design iterations, the unit is framed by two challenges: Students design a biosphere, a closed-system physical model that includes plants, snails, and guppies (a typical pet fish in the United States), and they program a computational model[2] that represents a larger ecosystem of plants, snails, guppies, and guppies' competitors and predators (Figure 1). Throughout the unit, the students gather information and re-represent the guppies' environment with increasing complexity. In this iteration of the design, invitations to engage in translanguaging during modeling were embedded within learning activities.

3.2 | Data sources

Data sources include whole-class and student-level data. We collected all student work, including sketches, diagrammatic and computational models, photos of physical models, and videos of students engaging in modeling and class discussions. These sources allowed us to trace the multiple modes, including languages, used by students in modeling. We used these data to analyze how students engaged in translanguaging and modeling throughout the 9-week unit.

For student-level data, focal students were selected with input from the school's sixth-grade teaching team to represent a range of backgrounds, academic performance, experience, and engagement. We used Camtasia software, which records students' computer screens and creates video and audio recordings with the computer's camera and microphone, to more closely follow the ways that these students engaged in classroom activities. We also conducted 25-min interviews with focal students to triangulate video data with students' experiences during the unit (see Appendix A for interview protocol). For focal students, we chose three bilingual students classified as ELs (Jennifer, Luis, and Carlos) and three monolingual students (Nora, Sam, and Alexis). We do not claim that these students' experiences are representative of all bilingual/EL students or all monolingual students, respectively, because we recognize the heterogeneity within both of these groups. Instead, we aimed to closely follow the way a few bilingual and monolingual students engaged in translanguaging and modeling to explore how these practices shaped opportunities for learning and engagement.

3.3 | Data analysis

Our retrospective analysis was initially based on the conjecture that connecting translanguaging and modeling would expand the resources that students could use for learning and engagement in modeling activities (see Figure 2, Conjecture Map). Whereas science classrooms have historically privileged "academic" English,

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TABLE 1 Sequence and summary of learning activities

Aligned Next Generation Science Standards (NGSS) and State Standards

Next Generation Science Standards
5-LS1-1. Support an argument that plants get the materials they need for growth chiefly from air and water.
5-LS2-1. Develop a model to describe the movement of matter among plants, animals, decomposers, and the environment.
5-PS3-1. Use models to describe that energy in animals' food (used for body repair, growth, motion, and to maintain body warmth) was once energy from the sun.
State Standards
6.LS2-1. Evaluate and communicate the impact of environmental variables on population size.
6.LS2-2. Determine the impact of competitive, symbiotic, and predatory interactions in an ecosystem.
6.LS2-3. Draw conclusions about the transfer of energy through a food web and energy pyramid in an ecosystem.

Activity	Modes/Models	Description
Day 1: What is a biosphere?	Discussion, text Video	• Watch a video about Biosphere2 • Discuss why biospheres are difficult to engineer • List variables that could be important to survival in a biosphere
Day 2–3: What do plants need to grow bigger?	Diagrammatic model Discussion, text Physical model	• Design/implement investigation to determine materials plants need to grow bigger
Day 4–6: What is a computational model?	Computational model Discussion Embodied model Physical model	• Compare and contrast biosphere models and computational models • Create guppy agents in a computational model • Create embodied programs of guppies swimming • Program guppies to swim in a computational model
Day 7: What do plants need to grow bigger?	Discussion Physical model	• Collect data from plant investigation • Discuss materials plants need to grow bigger
Day 8–12: What does a biosphere need to survive?	Computational model Diagrammatic model Discussion, text Physical model	• Read about carbon dioxide and oxygen cycle • Introduce and identify languages-of-modeling • Using evidence from plant investigation, research, and experience, design sustainable closed biosphere to support guppies • Build biosphere • Represent plants in computational models

(Continues)

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TABLE 1 (Continued)

Activity	Modes/Models	Description
Day 13–15: What do guppies need to survive in the wild?	Diagrammatic model Physical model Video	• Watch video about guppy research in the wild • Create diagrammatic model (food web) to represent energy pathways in guppies' environments • Compare wild guppies and their environment to biosphere models • Compare food web models in conversations orchestrated and brokered by the students
Day 16–17: How does energy flow in an ecosystem?	Computational model Diagrammatic model Discussion	• Represent the flow of energy between guppies and plants in a computational model, drawing on diagrammatic energy pathways • Create a sustainable system within a computational model • Discuss design principles for a sustainable environment
Day 18–19: How do other animals affect guppies?	Discussion Embodied model	• Enact predator/competitor relationships in embodied model
Day 20–21: How does energy flow in an ecosystem?	Computational model Discussion Physical model	• Add predators and competitors to a computational model, representing the flow of energy between organisms • Create a sustainable system within a computational model • Discuss design principles for a sustainable environment • Predict the effect of predators or competitors within biosphere models
Day 22–23: Why do we use different models?	Discussion Drawing/image, text	• Represent relationship between and affordances/limitations of diagrammatic, physical, and computational models with conversations between models

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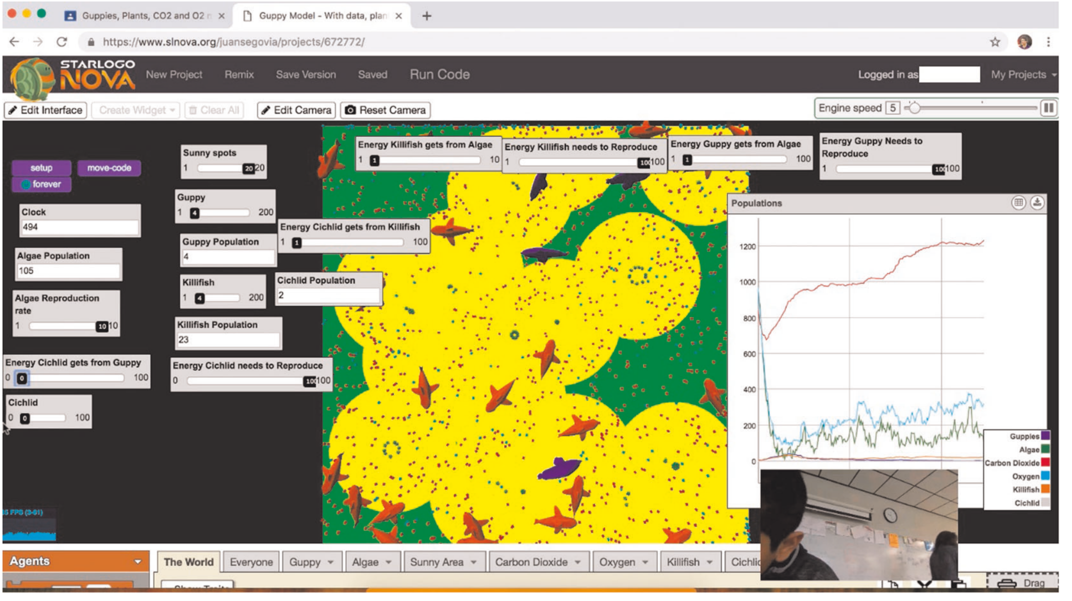

FIGURE 1 Computational model with algae (producer), guppies (consumer), killifish (competitor), and cichlids (predator). The sliders on the left control set-up parameters, the three-dimensional renderer in the center represent agent-level actions and interactions, and the graph on the right represents populations of each organism, as well as particles of oxygen and carbon dioxide available in the ecosystem. The stable state of this ecosystem was described by students as "fluctuate" or "balanciado" [Color figure can be viewed at wileyonlinelibrary.com]

we conjectured that connecting translanguaging and modeling would privilege other languages and modes, inviting students to use their full representational repertoires to participate in modeling activities. To evaluate our conjectures, we first analyzed how Ms. S introduced translanguaging in relation to modeling. Then, we explored how students took up the invitation to translanguage during modeling and how these practices shaped opportunities for learning and engagement.

To analyze teaching practices, we selected whole-class videos in which Ms. S explicitly introduced or invited translanguaging practices during modeling. To analyze students' engagement in translanguaging and modeling, we focused on activities in which students were encouraged to use multilingual and multimodal resources. In this analysis, we used videos of modeling activities recorded on students' computers along with students' end-of-unit interviews to triangulate our observations with students' perspectives and experiences. We transcribed each video, and we analyzed transcripts for themes related to teaching practices and students' translanguaging and modeling practices, as well as how these practices shaped students' opportunities for learning and engagement (Charmaz, 2006; Strauss & Corbin, 1990). We used these themes to revise our original conjectures (Cobb et al., 2003; Sandoval, 2014).

To contextualize students' engagement in translanguaging and modeling, we describe how Ms. S introduced and encouraged translanguaging in lessons co-designed by Ashlyn and Ms. S, based on the strategies from the theoretical framework and revised with feedback from a bilingual education researcher specializing in translanguaging (R. Jiménez, personal communication, January 7, 2019). Though translanguaging was introduced in whole-class discussions, students' modeling activities primarily took place in small groups of three or four students. In our analysis, we, therefore, analyzed these small groups as cases (Yin, 2014). In the Section 4, we present three cases that illustrate different approaches to translanguaging and modeling, and we consider implications for learning and engagement. Our analysis describes instances of translanguaging during modeling activities (including students engaging in modeling, as well as students reflecting on modeling during whole-class discussions,

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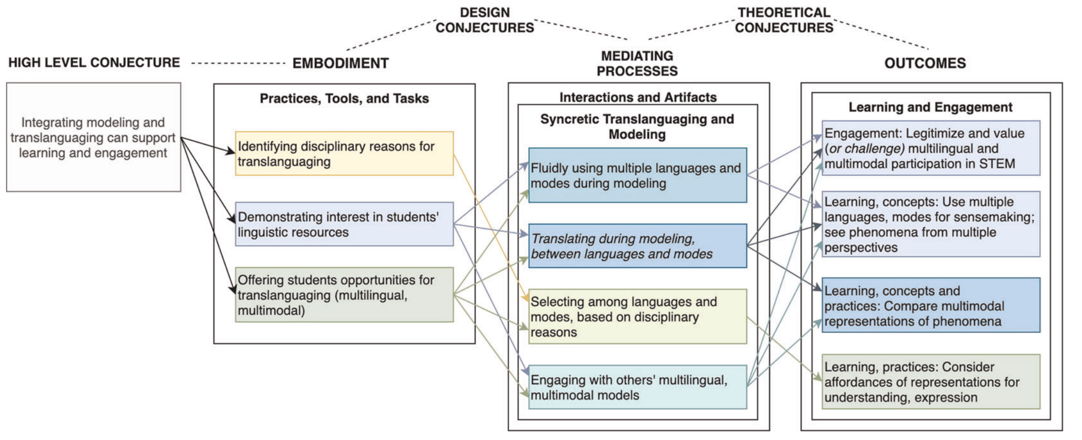

FIGURE 2 Conjecture map—Revisions based on findings from this study are represented with *italics* [Color figure can be viewed at wileyonlinelibrary.com]

interviews, or small group discussions). We conceptualized translanguaging broadly, including instances of students moving between modes (e.g., Williams, 2020) or named languages (e.g., Jiménez et al., 2015) and instances of students fluidly using multiple languages or modes to create or interpret models (e.g., Poza, 2018). From this perspective, all students (including "monolingual" students) engaged in forms of translanguaging. We focus on three cases that illustrate different ways that students interpreted and enacted translanguaging during modeling.

From the perspective of science-as-practice, science learning involves "learning to participate" in a scientific community (Lehrer & Schauble, 2015, p. 676). A "scientific community" is a group of people with shared values and tools and a shared purpose: creating scientific knowledge (Ford & Forman, 2006; Lehrer & Schauble, 2015). "Participating" in a scientific community involves developing practices for generating and evaluating scientific knowledge and using those practices to contribute to scientific knowledge. In this sense, conceptual knowledge and practices codevelop (Goodwin, 2017; Manz, 2012; Pickering, 1995). For example, exploring population dynamics (concept) through computational modeling (practice) can help students recognize and articulate affordances and limitations of computational models (e.g., computational models are not constrained by the "real world," so they can represent long-term, population-level interactions, but they may not be consistent with real-world data).

To describe students' engagement in modeling activities, we focus not only on students' individual actions (e.g., drawing, speaking) but also on interactions that reveal how students position themselves in relation to subject matter and other classroom participants (Cornelius & Herrenkohl, 2004; Goffman, 1981; Goodwin, 2017). For example, students might position themselves as language learners, or they might challenge the use of languages other than English in modeling; each stance shapes how students participate in modeling. Although we occasionally separate discussions of learning and engagement when describing how students took up invitations to translanguage during modeling, we recognize that these constructs are inextricably connected: Shifts in students' engagement are reflective of their learning (about ecosystems, and about "languages" and modeling generally).

4 | FINDINGS

In this section, we describe how Ms. S introduced translanguaging as a resource in her STEM classroom, and we present three cases that illustrate different ways that students (including students who identified as "bilingual" and "monolingual") took up this invitation. Our analysis will demonstrate that translanguaging has the potential to support new kinds of learning in English-dominant STEM classrooms, not only about STEM content and practices

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but also about what counts as legitimate and valuable participation in these spaces. Throughout the unit, Ms. S demonstrated that she valued students' multilingual and multimodal resources and offered students disciplinary reasons for using multiple languages and modes in modeling. Students took up these invitations to translanguage in different ways: By flexibly and fluidly using multiple languages and modes in their models, by translating during modeling, and by identifying and analyzing the multimodal resources within and across their models. Across all three cases, translanguaging supported learning and engagement for bilingual and monolingual students. Even so, our design did not always disrupt monoglossic ideologies or shift participant structures among students as intended, and we address challenges that emerged within our data.

4.1 | Invitations: Syncretic translanguaging and modeling

To introduce translanguaging as a resource in her English-dominant STEM classroom, Ms. S used approaches co-developed with Ashlyn based on several of the strategies described in the theoretical framework above: Specifically, demonstrating *interest in students' linguistic resources*, offering students *opportunities for translanguaging*, and helping students identify *disciplinary reasons for translanguaging*. These instructional strategies were proposed by the research team as a revision to the initial design of the unit, which previously allowed, but did not explicitly encourage, translanguaging. Ashlyn and Ms. S collaboratively planned each lesson, and Ms. S led instruction with support from Ashlyn.

The goal of our design was not to teach students *about* translanguaging or to teach them how to *"do"* translanguaging; instead, we aimed to support students in using a wider range of linguistic and nonlinguistic resources in service of sensemaking during modeling activities. We recognized that students were already intuitively drawing on available semiotic resources (including embodied actions and gestures) for meaning-making and expression, especially to facilitate fluid discourse (e.g., García, 2009; Williams, 2020). Even so, in this classroom, students had not previously used languages other than English in whole-class discussions, and they had not explicitly focused on the use of nonlinguistic representations in STEM. Below, we describe how Ms. S explicitly introduced translanguaging in discussions that took place on Days 8 and 9 of the unit, just before students began working on their biosphere plans.

Multimodal Translanguaging. On Day 8, Ms. S focused on multimodality in science to identify *disciplinary reasons* for translanguaging that would be accessible to all students. Although these discussions focused on language and representation, they were also generative for content learning, because they offered students new perspectives of their ecosystem models.

Ms. S began by framing multiple modes as "languages" in STEM, each with a unique disciplinary purpose. She opened the discussion by asking students to consider reasons for talking about language in science. Initially, students were unsure about "why we would talk about language in science class"—Sam said he was "not sure" and Eli focused on social interactions ("you don't want to use bad words or you could get in trouble"). Jesús's response moved toward a disciplinary reason for attending to language: "Because there's like complicated stuff like, in like, coding and stuff. There's like, different things, like vocabulary words. There's like different vocabulary words in like coding and science and all that other stuff."

To encourage students to broaden their perspective of language to include nonlinguistic modes, Ms. S asked students to "think about some ways that ideas are expressed" in their computational models. First, she asked students to identify modes within the computational model; then she encouraged students to identify a disciplinary purpose for each mode:

> Ms. S: What are some ways that ideas are expressed in this code? … What do you see Luna?
>
> Luna: A graph

Ms. S: You see a graph, okay good! And what does a graph do?

Luna: Shows you like your results.

Ms. S: Yeah, I love that, in what kind of way? Would you consider that words? There are kind of words there, but what would you consider that?

Carlos: Numbers.

Ms. S: There are numbers there, mm-hm. Can you look at it really quickly and go, "oh, I see what's happening here! That population is going down, right?" And so, if you can't see from the back, the green line here ((points to the graph)), this is plants, right, and then the blue is, that's the guppies. So just looking at that really quickly, what do you notice?

Luna: Plants are going up.

Above, Ms. S prompted students to attend to different modes. After students identified modes (e.g., "graph"), Ms. S asked for the purpose of specific modes (e.g., "what does a graph do?"). After eliciting student responses, Ms. S offered students an example of a disciplinary reason for using a graph ("can you look at it really quickly and go, 'oh, I see what's happening here?'").

After Ms. S shared this example, students identified reasons for using specific modes in other contexts, like the computational model:

Ms. S: What do you think this ((points to 3D renderer)) is representing?

Jennifer: Um the guppies and the plants and how they interact.

Ms. S: Yes, how they interact? Very good…but how is this [3D renderer]-how does this kind of talk to your brain differently than this [graph]? What do you think Jesús?

Jesús: Because um like the green thing [3D renderer] um like you have to look, and like, you have to actually count it.

Ms. S: ((laughs)) Right, right.

Jesús: You don't want to count all of that moving fish.

Above, Jennifer and Jesús described the complementary affordances of the 3D renderer (showing "how they interact") and the graph ("you don't want to count… moving fish"). This discussion thus encouraged students to recognize reasons for multiple modes (computer code, graphs, buttons, and sliders), and thus to value the use of different modes ("languages") in STEM.

Though the discussion focused on modes, it also led to opportunities for learning about population dynamics. For example, when considering why scientists might use sliders to control parameters in a computational model, Carlos considered interactions across three trophic levels:

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Carlos: Um, let's say, let's say that um, there's a bunch of plants and they live in a beautiful place with all the guppies inside. In one area, if we add–

Ms. S: Can you guys hear back there?

Students: ((nodding))

Carlos: And if there's like just five bass [potential predators] in one area, and if you add like five bass in every other area, and then they might eat the guppies, and the plants will be able to reproduce.

In this case, considering the purpose of the modes within the computational model also created an opportunity for Carlos to imagine population dynamics—specifically, how a predator (bass) might affect its prey (guppies) and lower trophic levels ("plants will be able to reproduce").

Through these discussions, Ms. S positioned nonlinguistic modes as legitimate and valuable for meaning-making and expression in STEM. These discussions set the stage for Ms. S to invite students to share their diverse linguistic resources the following day.

Multilingual Translanguaging. On Day 9, Ms. S shifted to focusing on "named" languages spoken by students in this class (English, Spanish, and Korean). Again, she focused on *disciplinary reasons* for using multiple languages. In addition, she *showed interest* in students' linguistic resources and *invited student to share* linguistic resources, including prioritizing contributions from bilingual students to legitimize the use of languages other than English in this context. Ms. S positioned herself as a language learner by asking students to repeat words that they shared and to help her pronounce words that were new to her. She also positioned students' contributions as important to the classroom community (rather than an answer solely for the teacher) by regularly asking students to restate their own or others' ideas. Although these conversations invited and legitimized the use of multiple languages, they may have inadvertently centered translation, because they focused on "untranslatable" words. To offer more fluid and flexible examples of translanguaging grounded specifically in STEM contexts, Ms. S and Ashlyn could have provided students with a form of *mentor text* (Seltzer, 2020; Zapata & Laman, 2016), such as a model that leverages multiple languages.

Ms. S opened this class by reminding students of their focus on language, then asking who "speaks two languages or more." Six students raised their hands: Eli (Korean and English), and Carlos, Jesús, Jennifer, Luna, and Luis (Spanish and English). Building on disciplinary reasons for multimodality established during the previous class, Ms. S prompted students to consider the affordances of languages by asking to students to share words "that are hard to tell, like, someone in English what it means." Eli offered two responses. First, he focused on pronunciation and writing: "Yes, so like 'mister.' You say 'mister,' but when you say it in Korean it's 아저씨… and then writing it is ((traces characters with gestures))." To emphasize how *meaning* can differ across languages, Ms. S asked "are there words in the Korean language that are totally, like, I don't even know how I would tell you this in English?" Eli responded:

So like um trying to explain food is a lot different than trying to explain like, when you're trying to explain like a food, like to explain smells and things, then like just say "I like rice," but then they'll go into descriptive almost.

With this response, Eli offered an example of how Korean can be more "descriptive" than English in some contexts, identifying differences between the languages and therefore a *reason* for using Korean (rather than translating to English) in these contexts.

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Next, Carlos shared two words that have context-dependent meanings in Spanish:

Carlos: So part of my family is from here, and part of my family is—so my Dad and all my other uncles are from Honduras and over there we speak a little bit different from them because they say "pajilla," like, for different things. Like "pajilla" is for—um for drinking [a drinking straw]. While we say—well, I don't really know what we really say because I don't speak that one [form of Spanish] very much anymore.

Ms. S: Do you know of any words that are hard to—like do you know any words that are hard to, so you speak Spanish—

Carlos: "Maje."

Ms. S: "Maje?" What does it mean?

Carlos: Um, "brother" ((laughs))

Ms. S: Okay but can you think of a word that really um it would be hard for you to describe to me what you're talking about, but I'm going to give you some examples in a minute.

Carlos's examples highlight how meaning can shift across contexts. First, he shared that there are multiple ways to say "drinking straw" in Spanish, including "pajilla." With this example, Carlos foregrounded the linguistic diversity *within* Spanish and *across* Spanish and English. Then, he offered another example—"maje," meaning brother. "Maje" is a complex term, because it can have a positive connotation for close friends, but a negative connotation otherwise. Because Ms. S and Ashlyn were unfamiliar with the term, they were not able to validate and help Carlos articulate this nuance at the moment; instead, Ms. S continued to ask Carlos to "think of a word that … would be hard for you to describe to me what you're talking about." This example underscores one of the challenges of supporting translanguaging for monolingual educators—it can be difficult to recognize and highlight the complexity in students' contributions.

To offer students examples of the affordances of different languages, Ms. S showed the students a short video about "untranslatable" words from different languages, frequently pausing the video to allow students to make connections to the words and the concepts they described. To help students recognize the affordances of different languages, she challenged students to think of words in English with the same meaning. Students offered words in English and Spanish:

Video: "…verschlimmbessern. That means that you try to make something better and it gets worse."

Ms. S: ((Pauses video)) Can you think of a word for that?

…

Eli: "Failure?"

Ashlyn: Carlos, did you have another word for trying to fix something but making it worse?

Carlos: "Arreglaro"—it means trying to fix, but it doesn't mean that it gets worse.

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Ms. S: Is there one that you can think of for try to fix it and it makes it worse? We've all done that right?

Sean: I tried to fix a drone, and it broke in half!

Ms. S: Can you think of a word though? [To Eli] Can you think of a Korean word?

Eli: No. I don't think Koreans want to focus on their failures!

Above, students offered several words to describe trying "to make something better and it gets worse," including "failure" and "arreglarlo," connecting the idea to their own experiences. Eli noted that there might not be a similar Korean word, explaining "I don't think Koreans want to focus on their failures!" With this observation, Eli imputed a role to culture in language use.

Throughout the discussion, Ms. S not only valued students' resources by inviting them to share terms but also demonstrated that she valued students' linguistic resources by encouraging students to help her learn and pronounce words:

Jesús: Tengo hambre.

Carlos: That's what I say all the time!

Ms. S: Say it again?

Jesús: Tengo hambre.

Ms. S: hambre

Jesús: Literally, I have hunger. Yeah, that's what I say when I'm hungry.

Above, Ms. S asked Jesús to repeat and help her pronounce "hambre," positing herself as a language learner and validating students' use of languages other than English in this classroom.

Ms. S also emphasized the value of students' contributions by asking students to restate their own and others' contributions to the discussion. For example, after discussing named languages, Ms. S asked students to compare linguistic and nonlinguistic resources. Jasper compared English and computer code, and Ms. S asked Nora to restate his idea:

Jasper: ... we told it [the computer]—we named the fish "guppy" and all of the sudden if we just use a different name it's not going to understand.

Ms. S: What did he just say Nora?

Nora: That if we use a different word for guppy it's not going to understand.

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In this case, Nora was able to hear and restate Jasper's contribution; in other cases, Ms. S asked students to repeat their idea so others could hear (facing their peers, standing, or using a louder voice). This positioned students' contributions as important in the class discussion, and it communicated to students that Ms. S was interested in their ideas and resources.

This discussion also offered students opportunities for domain-specific conceptual learning. When discussing how computer programming is different from English, Jesús asked:

> Jesús: What if we do like two objects [in the computational model] and we name both of them "fish" and we give both of them commands?
>
> Ms. S: could you do that?
>
> Jesús: One of them.
>
> Ms. S: I think some people did that.
>
> Ashlyn: Not quite. That's a great question because if you name two objects "fish," the computer wouldn't understand which one it was supposed to be talking to.
>
> Jesús: Will it do both or will it just do one?
>
> Ashlyn: …so it depends on the programming language we're doing…there are different results with different languages.
>
> Jesús: Oh, everything is about language.

In this case, considering the differences between English and programming led Jesús to new questions about computer code, adding depth to his understanding of programming.

After this discussion, Ms. S invited students to use multiple linguistic and nonlinguistic "languages" in the next activity: Designing their biospheres. She said, "the next thing we're going to do is to represent our biospheres, and … you can be creative with how you show your ideas." Directions for the assignment read: "We need to see (1) how everything will get energy and (2) how every living thing will get what it needs to breathe, oxygen or carbon dioxide. You can choose different languages or representations to show your ideas."

To explore the ways that students took up this invitation to translanguage, we present three cases that demonstrate distinct approaches to translanguaging that bilingual and monolingual students enacted. Following the cases, we describe a whole-class activity that built on students' use of "languages" in modeling.

Case 1: Multilingual and Multimodal Translanguaging

First, we show how one group engaged in translanguaging and modeling by fluidly representing ideas using a variety of linguistic and nonlinguistic modes. This flexibility is consistent with the way that translanguaging has been described by research in STEM classrooms. This group included two bilingual students (Carlos and Luis) and one monolingual student (Sean), and each student demonstrated preferences for different resources. Carlos and Luis fluidly moved between Spanish and English in their talk. Carlos was not confident about spelling in either language, so he focused on adding nonlinguistic modes; he added drawings to represent components of their biosphere, and he added string, sticker dots, and a numbering system to organize these components (Figure 3). Luis added most of the text to the model. Initially, he wrote primarily in Spanish, using English when he did not know a Spanish word to match an English word that he had learned in class. For example, he wrote, "El pes agara

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su comida de la planta y el *algae* y respira oxygeno" (the fish gets its food from the plant and the *algae* and breathes oxygen) on his model.[3] Luis's sentence blends English and Spanish words, and it also blends English and Spanish spellings (e.g., "oxygeno" rather than "oxygen" or "oxígeno"), demonstrating his expressive fluidity across languages.

Luis later translated his original text to English to make the model accessible to monolingual peers. However, his original, hybrid text often expressed more nuanced understandings of science content than the English translations. For example, in the statement above, Luis explained *how* the fish use plants and algae (as food) and oxygen (to breathe). In contrast, his English translation was "fish get energy from algae oxygen." Although the translation conveys that algae and oxygen are needed, it does not distinguish between their unique roles for the survival. This example suggests that accessing his full linguistic repertoire (fluidly blending Spanish and English) helped Luis express more nuanced ideas about science.

In addition to English and Spanish, the students used nonlinguistic modes for modeling. For example, when describing their biosphere plan during a gallery walk on Day 11, Luis said:

> I used English, Spanish, and pictures for languages. Then I have a key over here that uses stickers, and that's for the algae.... Then you have the fish, and you have the yellow stickers and then the fish is right here. And then, we just used different languages to describe what they use for energy, what they breathe in.

With this description, Luis identified linguistic modes (English and Spanish) as well as visual modes (drawings) and symbolic modes (stickers). Each mode offered different affordances for reasoning about the biosphere. For example, drawing the plant in the jar raised questions about the size of the plant and the space in the jar that were not considered when the students were initially talking and writing about their plan. While drawing, Luis explained the importance of the size of the plant to Sean: "We got a small plant... If we got a big plant, it would give it more oxygen and more food, but it would also need more carbon dioxide to survive, and it would have less space." This conversation also led to questions about the amount of space a guppy would need. During the gallery walk, Carlos explained that space could impact survival for guppies:

> When we searched it up it said that [guppies] could live two to three years, and then if we would have put in two guppies they would both probably die because it said for one guppy to live calmly, it would take one liter, and this isn't enough.

Thus, drawing not only offered students a new way to engage in STEM learning but also shifted their perspective to consider new aspects of guppies' wellbeing that might influence their survival, creating new opportunities for conceptual learning.

Framing modes within models as languages helped students make sense of other models as well. For example, in his interview, Carlos explained how multiple languages could "talk to each other" within the computational model:

> They talk to each other and combine to each other because if you look at this [the graph] it will show all the—the algae went down fast, so did the oxygen, oh but the algae went up again because of the death of the guppies, and then it shows that the cichlids are almost dead, died out, and the clock speaks because if you could tell the model if you set it up again, it starts at 1 and the population is 2 and those speak together because every time they move you could see, "oh, there's 6 cichlids, oh there's 6 guppies, oh it's been barely 17 or 18, 19 s."

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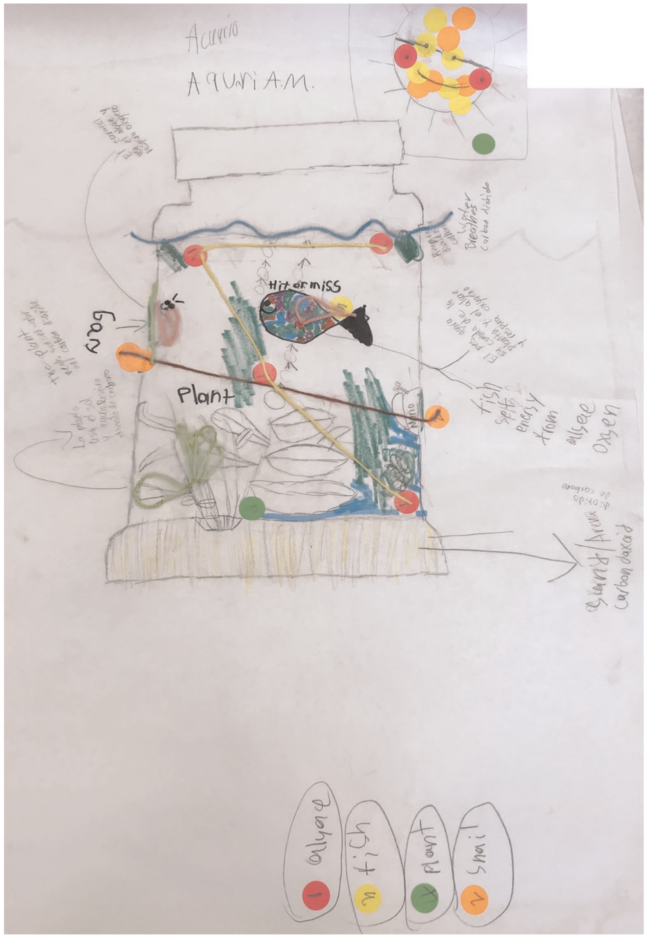

FIGURE 3 Luis, Carlos, and Sean's biosphere plan [Color figure can be viewed at wileyonlinelibrary.com]

Using a metaphor of modes "talk[ing] to each other," Carlos coordinated data from several dynamic modes to understand complex ecological interactions. He considered the relationship between two dynamic lines on the graph ("the algae went up again because of the death of the guppies"), the simulation ("it shows that the cichlids are almost dead"), and information from the clock and data boxes, which "speak together" to report the time and the population of each species. Thus, fluidly moving across modes helped Carlos make sense of the complex phenomena represented in the computational model.

Attending to modes within models also helped students consider the affordances of different model types. In his interview, Carlos compared the biosphere plan (a "paper" [diagrammatic] model) with the computational model:

> So compare this one [computational model] to the piece of paper. So this one helps out more because it moves. Paper could help out too because it stays still and you could copy it in real life. Then this one [computational model] you usually have to find a way to balance it, which is helpful. You can press set up and restart. On the paper, you can't press setup, you would have to erase it, but it's still really useful.

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Above, Carlos described *disciplinary reasons* for using multiple model types. He described computational models as dynamic tools that can be used to "balance" a population, and he identified a feature that makes computational models uniquely useful for inquiry (they can restart), an affordance also valued in professional science (cf. Nersessian, 2017). He also described the affordances of a paper (diagrammatic) model as a static tool —it "stays still and you can copy it in real life." Comparing representational resources, like computational and diagrammatic models, can inform students' representational choices in service of understanding and expression (e.g., diSessa et al., 1991; Pacheco & Smith, 2015), just as comparing linguistic resources can support students' development of metalingustic awareness (Jiménez et al., 2015). In this sense, syncretic translanguaging and modeling show promise for supporting not only conceptual learning but also learning about science practices (in this case, modeling).

As illustrated above, translanguaging and modeling created new opportunities for learning and engagement. Luis's hybrid text expressed more nuanced understandings about ecosystems than Spanish or English text alone. Moreover, speaking in Spanish and English offered Carlos and Luis access to their full linguistic repertoire for sensemaking. For Carlos in particular, attending to nonlinguistic modes offered new ways to contribute ideas to the biosphere plan. For all three students, multimodality offered new perspectives that shaped their learning about ecosystem (e.g., raising questions about space), and attending to multimodality showed promise for helping students parse and make sense of multimodal representations *within* models (explaining how modes "talk to each other" in the computational model) and *across* models (comparing reasons for using computational and "paper" models).

Despite these positive outcomes, Sean seemed at times to feel excluded when Luis and Carlos used Spanish. When working on the groups' biosphere plan on Day 10, Luis and Carlos initially used Spanish and pictures, limiting Sean's perceived opportunities to contribute. Sean said that he "can't read Spanish" and implied this prevented him from understanding the model:

> Sean: Why did you say algae?
>
> Luis: 'cause.
>
> Sean: You're pointing to a snail.
>
> Carlos: Yeah.
>
> Luis: The snail eats the algae, right? See that's what I put. ((pointing to "El caracol usa el algae y respira oxygeno"—The snail uses algae and breathes oxygen)).
>
> Sean: Well, I can't read Spanish!

In this interaction, Sean struggled to make sense of the representation, and he attributed this difficulty to the use of Spanish in the model. In response, he attempted to police the language in his group several times; for example, saying "Luis, just do it in English, we don't have to do Spanish." Sean's actions were not necessarily hostile, and they may have been well-intentioned—trying to understand and engage with Luis and Carlos. Regardless, these actions reflect and reproduce larger societal discourses that prioritize English over other languages.

In our data, only two students (Sean and Jasper) challenged the use of Spanish during modeling. Still, it is important to consider the ways that monolingual students might respond to multilingual practices because monolingual students also shape the practices that are valued and accepted within the classroom community. During class, this language-policing went unnoticed by Ms. S and Ashlyn, who are both white, monolingual English speakers. Although Ms. S and Ashlyn were both focused on trying to see, hear, and support students' multilingual

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and multimodal repertoires, their positionalities and experiences may have made it more difficult for them to recognize and respond to linguistic microaggressions at the moment. This example speaks to the broader challenges of shifting deeply entrenched linguistic ideologies (Flores & Rosa, 2015; K. Gutiérrez et al., 1995), particularly in English-dominant classrooms with monolingual teachers. To address these challenges, it is important to prepare, recruit, and support a population of teachers that reflects the diversity of the US student population and to provide support to educators to help them recognize and respond to systems of oppression in their classrooms.

In summary, translanguaging and modeling could create new opportunities for engagement in STEM by legitimizing multilingual and multimodal forms of expression. Attending to the "languages" within and across models shows promise for helping students parse and make sense of complex representations, like the biosphere and the computational model. Moreover, creating these multimodal representations could also help students recognize and explore new variables, just as drawing the biosphere helped this group consider the impact of space on plants' and guppies' survival. Even so, pedagogies that encourage translanguaging in an English-dominant classroom could be challenged by monoglossic ideologies. Further research is needed to understand how to frame these activities in a way that surfaces and addresses these ideologies to create more inclusive STEM learning environments.

Case 2: Translation within Modeling

Next, we present a case in which another group, also with two bilingual students (Jennifer and Jesús) and one monolingual student (Becca), took up the invitation to translanguage in a way that is more consistent with *translation* (García et al., 2020). This approach likely emerged in response to the emphasis on "untranslatable" words in the class discussion on Day 9, which foregrounded translating between named languages. The approach shifted opportunities for learning and participation in complex ways. Translating offered shifts in perspectives that led students to generative insights about ecosystems, both when translating from English to named languages (Spanish) or invented languages (computer "code-language"). Translating also shaped students' engagement in modeling activities. On one hand, these activities positioned Jennifer and Jesús as contributing to the group's model in unique and important ways; on the other hand, Becca maintained a leadership role within the group, managing students' contributions. Moreover, although these activities legitimized Spanish, translating initially seemed to reduce, then rebuild, Jennifer's confidence in her own linguistic resources.

When Becca, Jennifer, and Jesús began working on their biosphere plan, they chose to delegate a language to each student (Becca chose English, Jennifer chose Spanish, Jesús chose computer code—see Figure 4), and they translated each term in their model individually. This approach initially seemed to reify the idea of one-to-one correspondence between ideas and "correct" linguistic representations. However, "correctness" was problematized as Jennifer compared translations and built confidence in her linguistic resources, and Jennifer began to see translation as an opportunity for understanding science content in a new way.

Initially, Jennifer used Google Translate to "check" her translations, erasing her own translations (e.g., "piedras" for rocks) and replacing them with Google's ("rocas" for rocks). There was one exception: Jennifer had written "pescado hembra" and "pescado hombre," for female guppy and male guppy, but Google's translations were "pescado hembra" and "guppy masculino." Jennifer asked Jesús to help her select the "right" translation:

> Jennifer: Jesús, would this be right? "guppy masculino?" Or would it be "guppy hombre?" "Pescado hombre?"
>
> Jesús: Just put "hombre."
>
> Jennifer: Because female guppy it translated to "pescado hembra." But for the male… it should be "hombre."
>
> Jesús: Do "hombre"… "hombre," "hembra."

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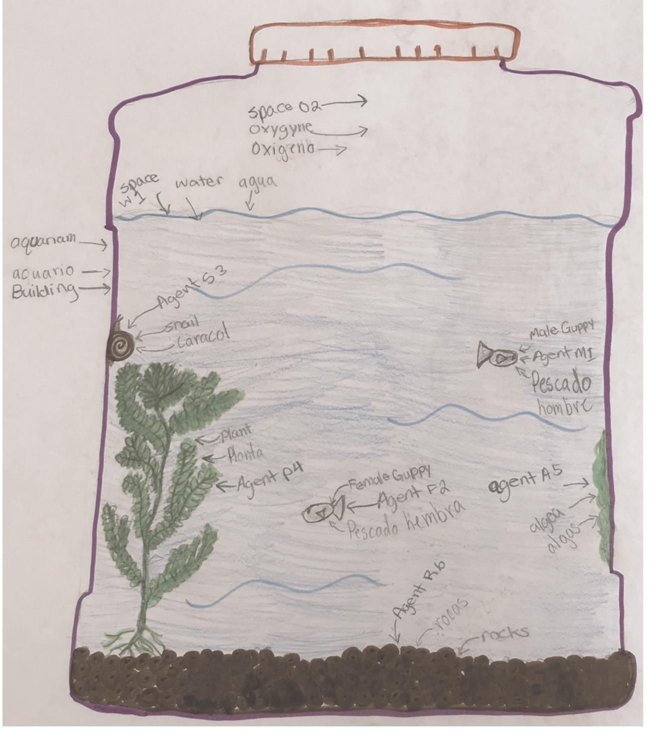

FIGURE 4 Jennifer, Jesús, and Becca's biosphere plan [Color figure can be viewed at wileyonlinelibrary.com]

Ultimately, Jennifer did not change “pescado hembra” or “pescado hombre,” possibly because of Jesús's affirmation or because she recognized Google's inconsistency

Jennifer's critical evaluation of Google's translations in this instance and others may have contributed to confidence in her own resources. Later, when working on a food web model, Jennifer used Google Translate for terms she did not know in Spanish (e.g., “algas” for “algae”), but she did not defer to Google's translations over her own. For example, her translation for “sun” (sol) remained even after Google provided “dom,” an incorrectly inferred abbreviation for “domingo” (Sunday). In this way, Jennifer simultaneously built confidence in the legitimacy of her own linguistic repertoire while expanding her repertoire to include new terms (e.g., algas).

In addition, Jennifer recognized translation as an opportunity to enrich and add nuance to her understanding of science content by helping her see phenomena from new perspectives. For example, in her interview, Jennifer explained how translating enriched her understanding of science content, even when she did not know the Spanish translation for an English term:

> In English, it's like “food chain” and you know, like, it has to be connected to something because of the word “chain,” and in Spanish, you have to think of, like, multiple words to describe the food chain because, like, in Spanish there's not really a word to describe food chain, so you have to, like—a sentence will describe a food chain, not just like saying two words.

Jennifer was not familiar with a Spanish term for “food chain” (e.g., “trófica” or “cadena alimentaria”), possibly because these terms are more common in academic rather than everyday settings. Even so, considering how to

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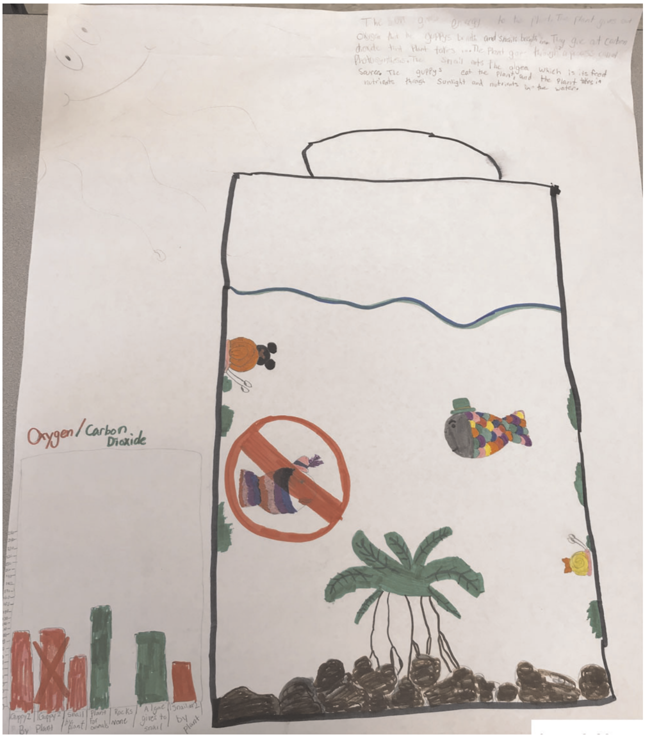

FIGURE 5 Jane, Kevin, and Nora's biosphere plan [Color figure can be viewed at wileyonlinelibrary.com]

translate the phrase created an opportunity for Jennifer to unpack and explore the meaning of "food chain," not only as a *term* but as a *representation* for an ecological phenomenon. She considered how "chain" connotes connection between organisms, facilitated by thinking of "multiple words to describe the food chain" in Spanish. Although we did not capitalize on this opportunity, it is possible that introducing Spanish terms like "trófica" could also help students learn cognate English terms (trophic), creating opportunities for bilingual language development.

While Jennifer worked on English-Spanish translations, Becca and Jesús created a language that mimicked computer code, which created an additional opportunity to engage in multilingual modeling. Broadly framing computer code as a language allowed Becca, a monolingual English speaker, to participate in a form of translanguaging. Whereas Becca's participation in modeling with multiple named languages was limited, creating a "code-language" was an opportunity for Becca to unpack English terms and the ideas they represented, similar to how Jennifer unpacked terms like "food chain" as she translated between English and Spanish. In addition, creating code-language offered Becca and Jesús a new way to express ideas, legitimizing linguistic resources beyond "academic" English and destabilizing English-only practices for monolingual and bilingual students.

To help Jesús, Becca asked Jennifer to use Google to "search up 'translate in code.'" Jennifer read the results: "Morse code, binary code, hex code…" Dissatisfied with these options, Becca and Jesús instead collaborated to create a computer "code-language":

> Becca: You need to label things in code. So what is the male guppy?
>
> Jesús: GuppyM.

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Becca: Agent1 right?

Jesús: Oh no, AgentM!

Above, Becca and Jesús began creating a system for naming the objects in their invented code language. In the process, they classified objects in the biosphere plan into abstract types, and they numbered each instance. They used "agent" to describe visible discrete components of the biosphere, like guppies and algae. The word "Agent" was followed by a letter that described a salient attribute of the agent – either the type of object ("S" for snail) or a more specific attribute ("F" for female guppy and "M" for male guppy):

Becca: This would be AgentF ((points to the female guppy)), AgentS ((points to the snail)).

Jesús: AgentS, water is AgentW.

Becca: Yeah!

A few components were not considered agents—the jar ("building") and the types of space within the jar ("spaceO2"):

Jesús: I don't know what this aquarium would be called.

Becca: Is there like a building? Are there, like, buildings in there?

Jesús: Watch… I'm just going to call it aquarium.

Becca: No, call it building. You tell me and I'll write it down, ok?

Modeling the biosphere by classifying its components created categories that would not have been evident with English or Spanish labels alone. Jennifer, who was not involved in creating the code-language, noted this affordance both in her presentation of the biosphere plan in a gallery walk and in her interview 2 months later, describing the code-language as "specifying things more" than English and Spanish. Thus, creating code language was an opportunity for students to express ideas and develop a precise articulation and understanding of the components of the biosphere and how they were related to each other.

In this case, students took up invitations to translanguage by focusing on translating terms in their models in ways that both expanded and limited students' opportunities for learning and engagement. Translating to Spanish and to "code-language" shifted students' perspectives of phenomena, helping Jennifer develop more nuanced understandings of concepts (e.g., "food chain") and enabling Becca and Jesús to develop a taxonomy that classified components of their biosphere. These activities legitimized resources beyond "academic" English, enabling students to draw on resources such as Spanish and creative linguistic and symbolic representations.

This interpretation of translanguaging and modeling also shaped participant structures, and, therefore, engagement in this group. Although Jennifer was responsible for Spanish, she included Jesús in conversations about her translations (e.g., how to translate male/female guppy), particularly when her own translations differed from those suggested by Google Translate. In contrast, as a monolingual English speaker, Becca's contributions were limited in these conversations. Following Ms. S's example, Becca at times asked Jennifer and Jesús to help

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her pronounce or translate Spanish words, demonstrating that she valued these contributions and positioning herself as a language learner. Though this activity positioned Jennifer as having a unique and important role in the model, being responsible for Spanish may also have limited her engagement in other ways—because Jennifer was focused on Spanish translations, she was less involved in the development of the computer code language than Becca and Jesús.

Adding computer code language to the model led to different dynamics. Though code language was accessible to all of the students in the group, Becca's access to this activity reified typical participant structures in the group rather than challenging these structures. Although translating to code language was Jesús's job, Becca ultimately led the task. She asked for Jesús's input and showed that she valued his suggestions by adopting some of them (using letters to specify agent types). Still, Becca ultimately made decisions about what was written on the biosphere plan (e.g., "building" and "spaceO2"). In this case, inventing language, like code-language, created new opportunities for learning and engagement; however, the activity did not shift participant structures in the same way as adding Spanish to the model did.

In summary, students, in this case, interpreted the invitation to use multiple "languages" in their model as a translation activity, and they translated terms across named languages (Spanish and English) and invented languages (computer code language). This approach shows promise for supporting learning by helping students unpack the meaning of science concepts as they consider multiple translations and perspectives of phenomena. Yet, pedagogies that adopt an exclusive focus on translation may fall short of goals of creating more equitable learning environments. Translating to *named* languages offers new forms of engagement for bilingual students but could inadvertently emphasize "correct" translations, decreasing bilingual students' confidence in their linguistic resources rather than encouraging them to leverage these resources in fluid ways that support sensemaking. Translating to *invented* languages shows promise for helping monolingual students feel included in translanguaging and modeling activities but may not disrupt participant structures in which monolingual students take on leadership roles. Further research is needed to understand how to leverage pedagogies of *translation* in ways that support STEM learning and engagement for both bilingual and monolingual students.

Case 3: Translanguaging for "Monolingual" Students

In this third case, we explore how introducing translanguaging during modeling shaped opportunities for learning and engagement for groups composed entirely of "monolingual" students. In these groups, attending to "languages" within models created space for diverse representations that helped students consider the affordances of canonical representations (e.g., energy pyramids) as well as less conventional representations. Although students were not necessarily critical of disciplinary modeling practices, attending to the unique strengths of multiple representations was *expansive*—students recognized disciplinary reasons for using multiple representations rather than focusing on one "correct" way to represent an ecosystem. This stance enabled students to carefully attend to meaning in their own and others' models, and it created opportunities for students to reflect on and evaluate the representations they designed (diSessa et al., 1991; Enyedy, 2005; Lehrer & Schauble, 2012; Sengupta et al., 2021). Moreover, emphasizing multimodality created increased opportunities for all students to participate in modeling, including students with disabilities that limited their verbal communication.

Even in "monolingual" groups, students described the linguistic and nonlinguistic modes in their models as "languages." For example, when describing her group's biosphere plan (Figure 5), Nora explained that her group (Nora, Jane, and Kevin) used several modes that were each "different in their own way":

> Nora: When we were doing the model… we used a graph to show what was getting oxygen, and what was getting carbon dioxide, and we used pictures and English as *languages*.
>
> Ashlyn: mm-hmm and do those all- like the pictures and English and graph—do those all show the same thing in a different way, or do they show like slightly different things?

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Nora: Um they well- when we were using English it was just at the top of our paper. We kind of just wrote a paragraph. We kind of talked about how it's getting energy, so it's kind of similar to the graph, which it's saying what takes in oxygen and carbon dioxide… And the picture was just showing like, to know what is what, kind of. So they're kind of similar but different in their own way…like when we're drawing our biosphere, we couldn't see the Sun actually giving energy to the plant, but for us when we wrote it out, I was like "okay"—like if it was a different group, I was like "okay I- now I know that the sun is giving, um, energy to the plant and then plant is going through photosynthesis," which you couldn't see in a drawing.

Above, Nora identified different modes from her group's biosphere plan, describing a unique purpose for each mode—the paragraph explained how organisms obtained energy ("which you couldn't see in a drawing"), the bar graph showed how much oxygen and carbon dioxide were needed, and the pictures represented the components of the biosphere.

During the gallery walk, Jane and Nora also attended to the languages that other groups used in their models and the ideas they represented. When visiting Luis's group, Jane asked:

Jane: What is the Spanish here?

Luis: So right here, it says in Spanish, it says, "The plant needs sun and water and carbon dioxide." In Spanish, it says "La planta usa el sol y agua. Respira dióxido de carbono."

Jane: I like how you used different languages, that's very good.

Jane demonstrated interest in Luis's use of Spanish, framing his use of "different languages" as valuable in this context. Meanwhile, Nora focused on the content of the model. She listened as Carlos explained, "We didn't include two-two guppies, because online it said that for one guppy to live in, it takes one gallon, so if we would have gotten two guppies it would have taken two gallons, which we couldn't hold." Later, when Nora visited Jennifer's group, she asked:

Nora: Is there a reason for two fish?

Jennifer: It said they're better off living in pairs so we decided to get two to be more at home.

Nora: Yeah I know some groups [Luis, Carlos, Sean] did one, because they said the guppy needs space.

Afterward, Nora suggested to Jane and Kevin that they change their own plan to include one guppy rather than two because she was concerned about having enough space. Ultimately, the group revised their plan, crossing out their second guppy. In this case, the students' multimodal models served as a medium for students to share and revise ideas about their biospheres.

In particular, the biosphere plans offered Kevin and Darius, two students with disabilities that limited their verbal communication, a way to engage with their peers' ideas and participate in designing their groups' models. Kevin and Darius helped with their groups' plans by drawing, arranging cut-outs of biosphere components, and using gestures or assistive technology to express agreement or disagreement when asked about changes to the

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plans (e.g., “do you like having one fish instead of two?”). Thus, rather than working on separate tasks (as was typical during STEM), Kevin and Darius were able to engage in modeling with their peers.

During the gallery walk, being able to point to parts of the biosphere plans helped Darius engage with other groups' ideas. When visiting Nora, Jane, and Kevin's group, Ms. A (a paraprofessional supporting Darius) helped Darius recognize components of another group's biosphere plan that were similar to his group's plan:

> Ms. A: Look! Darius, you have guppies, a snail, rocks, what else we got? Where's the snail?
>
> Darius: Snail ((points to snail)).
>
> Ms. S: Where's the rocks?
>
> Darius: Rock.
>
> Ms. A: Where's the fish? Guppies? Show me.
>
> Darius: ((Points to guppies))
>
> Sam: Good job, Darius ((Sam and Darius high-five)).

Above, Ms. A and Darius worked to make sense of another groups' biosphere plan by identifying components of the model. In this activity, focusing on multimodal “languages,” thus, expanded opportunities for Darius and Kevin to engage in classroom modeling by offering visible and tangible resources for meaning-making and expression.

Furthermore, attending to meaning represented within specific models enabled students in this classroom to take on a more expansive stance toward models, helping them attend to strengths in canonical and unconventional representations rather than prioritizing one “correct” representation. For example, when creating food webs to represent the guppies' ecosystem, Sam noticed that his group (Alexis, Darius, Jack, and Sam) had used arrows in a different way from another group. Canonically, arrows in a food web point from an energy source to the organism (s) acquiring energy; the other group used arrows in this conventional way. In Sam's group's model, arrows instead pointed from an organism to what that organism ate. When presenting the model, rather than framing one model as “more correct” or “better” in an absolute sense, Sam described how each model showed a different way of understanding energy transfer: “On ours, it shows what each animal eats, and on theirs, it shows what energy it gives off to different animals.”

Other groups also identified unique representational affordances of their models. For example, when Nora and Sean compared their groups' models, they described the different ideas that their models foregrounded. Nora introduced the models: “This one, ours, is more like an energy pyramid, and it shows what is giving off energy, and theirs is more environmental.” Sean unpacked “more environmental,” explaining, “here you can see the fish live in the water, and the birds in the sky and the tree,” describing how his group's model foregrounded the relationship between organisms and their habitats. By putting their models in conversation, the students were able to recognize a disciplinary reason for each representation—the unique ideas foregrounded by Nora's energy pyramid and Sean's environmental representation.

Focusing on disciplinary reasons for representations also helped students compare different types of models. For example, in her interview, Alexis compared the biosphere model with the embodied model. She said the biosphere was:

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> A better explanation than just the plant [investigation] and the one on paper because it was kind of like a whole little ecosystem in itself, so we could see, like, how the sunlight affected the fish and how that kind of affected the plants and how that grew.

Although the biosphere offered a “better explanation” because it contained a “little ecosystem,” Alexis also recognized a limitation of the biosphere complemented by the computational model:

> Alexis: It better showed how things- how when adding, like, another predator of something into an ecosystem can decrease it because when we added the cichlid [predator] it took down the killifish which made the algae grow larger… because it would be difficult to see in the water and watch it happen.
>
> Ashlyn: You can see it easier in the computational model?
>
> Alexis: Yeah, and because it goes faster.

Above, Alexis compared models and considered the disciplinary reasons for using multiple models to make sense of ecosystems. In this sense, emphasizing modeling and translanguaging in STEM shows promise for supporting all students, including monolingual students, in valuing and learning from multiple representations of phenomena. This perspective encourages students to parse complex models and model systems to identify what each uniquely contributes to their understanding of systems and phenomena in the world, creating opportunities for students to reflect on representational forms and how they might be useful for producing knowledge.

In summary, although translanguaging is typically seen as a pedagogical approach that supports multilingual students, our data suggest that connecting translanguaging and scientific modeling (with an emphasis on multimodality) also supported monolingual students, including students with disabilities that limited their verbal communication. Multimodal representations can make learning more inclusive by offering additional channels for students to express, share, and refine their ideas. Moreover, identifying strengths of different representations positions modeling as an expansive practice that enables students to try on new perspectives of phenomena (e.g., focusing on energy transfer vs. environmental niches in a food web). This approach positions multiple representations as valuable, and it encourages students to reflect on the contexts in which particular representations could be useful. As they are introduced to new linguistic resources by their peers and as they see their teacher demonstrate an interest in diverse languages, “monolingual” students may also become interested in expanding their own repertoires to include new languages. In this classroom, a few students (e.g., Becca and Jane) asked their peers to share Spanish words and phrases, yet not all monolingual students positioned themselves as language learners. Further research is needed to explore how to support monolingual students in engaging in multilingual aspects of translanguaging and modeling.

4.2 | Repeated invitations for translanguaging

Throughout the semester, Ms. S continued to encourage students to use multiple “languages,” including non-linguistic modes, as they created models of ecosystems. In some cases, Ms. S simply reminded students of the option to use different languages in their models. In other cases, Ms. S more explicitly and deliberately invited students to draw on linguistic resources beyond “academic” English for sensemaking. These activities legitimized the use of a wider range of resources in STEM and created new opportunities for learning science content.

For example, as students explored population dynamics in their computational models on Day 17, Ms. S asked students to create a “class term.” Shared language had not yet emerged to describe the pattern in the computational models' graphs when an ecosystem was relatively stable (see Figure 1), although this phenomenon is central to population dynamics. When asked to describe this pattern, students often mimicked the shape of the graph with a hand gesture. For example, Jasper used a gesture to describe his graph at the beginning of class:

> Ms. S: What do you notice when they're surviving long term?
>
> Jasper: Mine have been ((graph gesture)) and up, up, up. Then oxygen and carbon dioxide go up and down.

As this phenomenon became central to students' discourse, Ms. S asked students to nominate English, Spanish, and invented terms to describe the pattern, legitimizing linguistic resources beyond “academic” English. All groups nominated at least one English term, two groups presented a Spanish term, and all groups created and justified at least one invented term. For example, Eli shared an invented term: “Flectorate. It sounds like fluctuate, and it means the rates are changing.” Luis offered English, Spanish, and invented language: “We did fluctuate, balanciado, and we also made up a word. It's from balanced and graph. It's a balagraph.” These examples demonstrate the wealth of linguistic resources that students brought to interpreting and describing the pattern. This activity enabled students to draw on their full linguistic repertoires to consider what was salient about the pattern, enriching their understanding of the phenomenon. Moreover, these terms stabilized a way of interpreting the graphs in the computational model, helping students make sense of these canonical representations.

The invented terms were rarely used in whole-class discourse after Day 17 (possibly because the invented terms were not taken up by Ms. S and Ashlyn, who could have worked to legitimize these terms by adopting them in their own discourse). However, the English and Spanish terms did appear in small-group and whole-class discussions. For example, on Day 20, students shared strategies for sustaining complex systems in their computational models. Amanda used class terms (balance and fluctuate) to describe what she observed: “If there is *balance*, there will be some spikes, but they aren't going to go too drastically high or too drastically low. And if they do go a little bit up, they go back down. So basically, it *fluctuates*.” As she said “fluctuates,” she used the graph gesture, coordinating multimodal resources created by the students to express an idea about population dynamics. The “class terms” activity thus leveraged translanguaging and modeling in a different way from the cases above, inviting students to use their full linguistic repertoires to make sense of a canonical, nonlinguistic representation (a graph) and the real-world phenomenon it represents (a stable ecosystem).

5 | DISCUSSION AND CONCLUSIONS

The findings above demonstrate that translanguaging has the potential to support new kinds of learning in English-dominant STEM classrooms, not only about STEM content and practices but also about what counts as legitimate and valuable participation in these spaces. A wealth of research demonstrates that translanguaging can support science learning in bilingual classrooms (e.g., Licona & Kelly, 2019; Poza, 2018), yet, to our knowledge, few studies have explored strategies for inviting and leveraging translanguaging in English-dominant STEM classrooms. Drawing on teaching practices that have been shown to support multilingual and multimodal composing primarily in literacy classrooms (e.g., L. W. Rowe, 2018; Smith et al., 2020), we aimed to design learning activities that would invite and support translanguaging as part of scientific modeling. Specifically, we explored how scientific modeling could not only provide a context for translanguaging but also provide a setting where modeling and translanguaging could be experienced as analogous meaning-making practices.

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To this end, our designed learning activities encouraged students to leverage their full linguistic and non-linguistic repertoires. Throughout the unit, Ms. S demonstrated that she valued students' resources (García & Kleifgen, 2019; L. W. Rowe, 2018) and offered students disciplinary reasons for using multiple languages and modes in modeling (Canagarajah, 2013; García & Kleyn, 2016). Students took up these invitations to translanguage by flexibly and fluidly using multiple languages and modes in their models, translating during modeling, and identifying and analyzing the multimodal resources within and across their models. We consider these approaches syncretic (K. D. Gutiérrez & Jurow, 2016) because they enable students to engage in more equitable forms of STEM learning that are distinct from the ways that translanguaging and modeling practices are described in bilingual education research and science education research, respectively. Translanguaging research often focuses on linguistic resources and multilingual classrooms rather than emphasizing multimodal resources and including monolingual students. Modeling practices are often multimodal, but they less often explicitly invite and leverage students' full linguistic repertoires, including named languages (in this case, Korean and Spanish) and students' invented terms. Our findings thus demonstrate that syncretic modeling and translanguaging practices have the potential to be transformative of STEM learning and engagement, but they also surface challenges that should be addressed in future research.

Across all three cases, translanguaging supported learning and engagement for bilingual and monolingual students. Using multiple languages enabled students to express ideas with specificity (Luis, with hybrid Spanish and English text), unpack science terms and concepts (Jennifer, Becca, and Jesús, translation to new and invented languages), parse and make sense of complex representations (Carlos, computational model), recognize new relevant variables in their models (across cases, identifying "space" as a variable important to guppies survival), express ideas and engage with others' ideas (Kevin and Darius, with visual modes), and identify disciplinary reasons for using multiple representations (Carlos, Alexis, comparing biospheres and computational models). Although students took up invitations to translanguage in different ways, each of these approaches offered students new perspectives of phenomena, a wider range of multilingual and multimodal channels for making sense of phenomena, and enhanced opportunities to compare and consider the affordances of modes and model types.

Furthermore, translanguaging and modeling made space for students to shape inquiry and knowledge production in the classroom, creating a more equitable environment for science learning (Bang et al., 2012; Haverly et al., 2018; Rosebery et al., 2010). Rather than reproducing canonical representations, creating multiple, multimodal representations led students to ask and explore questions that were not intended or anticipated as part of the unit. For example, students considered the role of variables that were not addressed in the learning objectives (Cases 1 and 3, the role of "space" in guppies' survival). Translanguaging was also taken up in unexpected ways by students (Case 2, translating across named and invented languages). In this sense, the design enabled students to exercise agency in shaping classroom inquiry and representational practices. As a result, rather than creating representations that were always aligned with disciplinary norms, students at times created representations that challenged conventions (Case 3, arrows pointing to what was being eaten in the food web, food webs organized by environmental niches rather than flow of energy), and students recognized the value in both canonical representations and creative, invented representations.

Because we aimed to support more equitable engagement in STEM learning in this English-dominant classroom, a goal of the designed learning activities was to position translanguaging as an important part of modeling for all students rather than as a scaffold for emergent bilingual students. Therefore, we emphasized multimodality as a way that monolingual students could participate in translanguaging. Beyond multimodality, some students, like Becca and Jane, also demonstrated interest in linguistic resources that were new to them, following Ms. S's example by asking their peers to share and help them pronounce new words. Even so, our design did not always disrupt monoglossic ideologies or shift participant structures as intended. For example, we described in Case 1 how Sean challenged the use of Spanish, and we described in Case 2 how translating initially *decreased* Jennifer's confidence in her own linguistic resources and enabled Becca to maintain her leadership role in the group. To more systematically counter monoglossic linguistic ideologies that center English, designs for learning could offer opportunities to critically reflect on the dominant discourses and practices in STEM that have historically excluded diverse linguistic and epistemic resources. Beyond curriculum, it is important to prepare, recruit, and support a population of teachers that reflects the diversity of the US student population and to provide support to educators to help them recognize and respond to systems of oppression in their classrooms.

These challenges reinforce that there is still much to learn about designing to support inclusive and equitable science learning environments, particularly in linguistically diverse classrooms. Even so, these findings demonstrate the transformative potential of connecting translanguaging and modeling to support learning and engagement for all students, including bilingual and monolingual students, in English-dominant STEM classrooms.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ENDNOTES

[1] From the perspective of translanguaging theory, "bilingual" and "monolingual" are socially constructed concepts; there is no threshold of linguistic knowledge that distinguishes between monolingual, bilingual, and multilingual students. Still, these categories are important in discussions of social identity and sociolinguistic behavior (Otheguy et al., 2015). In this study, we use "bilingual" to describe students who identified as bilingual and used more than one language (in or out of school), including students who were classified as English learners. We use bilingual rather than multilingual because we did not observe any students drawing upon more than two languages in the data we collected. We use "monolingual" for students who did not identify as bilingual and used English almost exclusively for speaking and writing. We recognize that "monolingual" students can leverage other multimodal resources, like gesture and drawing, and sometimes use resources from languages other than English.

[2] In this study, we used an agent-based modeling environment, StarLogo Nova (SLN), to help students explore population dynamics in ecosystems. Agent-based models begin by modeling the micro-level actions and interactions of system components (the "agents") and then instantiate large numbers of these agents to simulate macrolevel aggregate behaviors of the system as a whole. SLN combines a block-based programming environment with an agent-based simulation engine and a 3D renderer that depicts agent-agent interactions in a virtual world optimized for modeling complex systems. SLN also includes the ability to use tables and graphs to visualize data. In the data analyzed below, we note how students refer to components of SLN models, using the components' names, such as "3D Renderer" or "graph."

[3] In our data, we preserve students' spelling and grammar in written text, both in English and in Spanish.

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REFERENCES

Ag, A., & Jørgensen, J. N. (2013). Ideologies, norms, and practices in youth poly-languaging. *International Journal of Bilingualism*, *17*(4), 525–539.

Ainsworth, T., & Prain (2020). Learning by construction of multiple representations. In Van Meter, P., List, A., Lombardi, D. & Kendeou, P., *Handbook of learning from multiple representations and perspectives* (pp. 92–106). Routledge.

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Anzaldua, G. (1987). Chapter 5: How to tame a wild tongue, *Borderlands, La Frontera: The new mestiza*. Aunt Lute Books.
Baker, C. (2011). *Foundations of bilingual education and bilingualism* (Vol. 79). Multilingual matters.
Bang, M., Warren, B., Rosebery, A. S., & Medin, D. (2012). Desettling expectations in science education. *Human Development*, *55*(5–6), 302–318.
Barajas-López, F., & Bang, M. (2018). Indigenous making and sharing: Claywork in an indigenous STEAM program. *Equity & Excellence in Education*, *51*(1), 7–20.
Bezemer, J., & Kress, G. (2008). Writing in multimodal texts: A social semiotic account of designs for learning. *Written Communication*, *25*(2), 166–195.
Blackledge, A., & Creese, A. (2017). Translanguaging and the body. *International Journal of Multilingualism*, *14*, 1–19.
Brady, C., Orton, K., Weintrop, D., Anton, G., Rodriguez, S., & Wilensky, U. (2016). All roads lead to computing: Making, participatory simulations, and social computing as pathways to computer science. *IEEE Transactions on Education*, *60*(1), 59–66.
Bucholtz, M., & Hall, K. (2005). Identity and interaction: A sociocultural linguistic approach. *Discourse Studies*, *7*(4-5), 585–614.
Canagarajah, A. S., (Ed.). (2013). *Literacy as translingual practice: Between communities and classrooms*. Routledge
Charalambous, P., Charalambous, C., & Zembylas, M. (2016). Troubling translanguaging: Language ideologies, superdiversity and interethnic conflict. *Applied Linguistics Review*, *7*(3), 327–352.
Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. Thousand Oaks, CA: Sage.
Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, *32*(1), 9–13. https://doi.org/10.2307/3699928
Cole, M. W., David, S. S., & Jiménez, R. T. (2016). Collaborative translation: Negotiating student investment in culturally responsive pedagogy. *Language Arts*, *93*(6), 430.
Cornelius, L. L., & Herrenkohl, L. R. (2004). Power in the classroom: How the classroom environment shapes students' relationships with each other and with concepts. *International Journal of Bilingual Education and Bilingualism*, *22*(4), 467–498. https://doi.org/10.1207/s1532690Xci2204_4
Daniel, S. M., Jiménez, R. T., Pray, L., & Pacheco, M. B. (2019). Scaffolding to make translanguaging a classroom norm. *Tesol Journal*, *10*(1), e00361.
di Sessa, A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior*, *10*(2), 117–160.
Domínguez, H. (2011). Using what matters to students in bilingual mathematics problems. *Educational Studies in Mathematics*, *76*(3), 305–328.
Durán, L. (2016). Revisiting family message journals: Audience and biliteracy development in a first-grade ESL classroom. *Language Arts*, *93*(5), 354–365.
Durán, L. (2017). Audience and young bilingual writers: Building on strengths. *Journal of Literacy Research*, *49*(1), 92–114.
Enyedy, N. (2005). Inventing mapping: Creating cultural forms to solve collective problems. *Cognition and Instruction*, *23*(4), 427–466.
Espinosa, C. M., & Herrera, L. Y. (2016). Reclaiming Bilingualism: Translanguaging in a Science Class. In O. García, & T. Kleyn (Eds.), *Translanguaging with multilingual students: Learning from classroom moments* (pp. 160–178). Routledge.
Esquinca, A., Araujo, B., & de la Piedra, M. T. (2014). Meaning-making and translanguaging in a two-way dual-language program on the US-Mexico border. *Bilingual Research Journal*, *37*(2), 164–181.
Farris, A., Dickes, A. C., & Sengupta, P. (2020). *Grounding Computational Abstractions in Scientific Experience. In Proceedings of the International Conference of the Learning Sciences* (Vol. 3, pp. 1333–1340). International Society of the Learning Sciences.
Flores, N., & Rosa, J. (2015). Undoing appropriateness: Raciolinguistic ideologies and language diversity in education. *Harvard Educational Review*, *85*(2), 149–171.
Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education*, *30*, 1–32.
Gallo, S., Link, H., Allard, E., Wortham, S., & Mortimer, K. (2014). Conflicting ideologies of Mexican immigrant English across levels of schooling. *International Multilingual Research Journal*, *8*(2), 124–140.
García-Sánchez, I. M. (2016). Multiculturalism and its discontents: Essentializing ethnic Moroccan and Roma identities in classroom discourse in Spain. In H. Samy Alim, J. Rickford, & A. Ball (Eds.), *Raciolinguistics: How language shapes our ideas about race* (pp. 291–308). Oxford University Press.
García, O. (2009). Emergent bilinguals and TESOL: What's in a name? *Tesol Quarterly*, *43*(2), 322–326.
García, O., Aponte, G. Y., & Le, K. (2020). Primary bilingual classrooms: Translations and translanguaging. In S. Laviosa, & M. González Davies (Eds.), *The Routledge handbook of translation and education* (pp. 81–94). Taylor and Francis.
García, O., & Wei, Li (2014). *Translanguaging: Language, Bilingualism and Education*. New York, NY: Palgrave MacMillan.
García, O., Johnson, S., & Seltzer, K. (2017). *The translanguaging classroom: Leveraging student bilingualism for learning*. Caslon.
García, O., & Kleifgen, J. A. (2019). Translanguaging and Literacies. *Reading Research Quarterly*, *55*(4), 553–571.

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García, O., & Kleyn, T. (2016). Chapter 1: Translanguaging theory in education. In O. García, & T. Kleyn (Eds.), *Translanguaging with multilingual students: Learning from classroom moments* (pp. 9–33). Routledge.
Goffman, E. (1981). Footing. In Goffman, E., *Forms of talk* (pp. 124–159). University of Pennsylvania Press.
Gooding, D. C. (2006). From phenomenology to field theory: Faraday's visual reasoning. *Perspectives on Science*, *14*(1), 40–65.
Goodwin, C. (2017). *Co-operative action (Learning in doing: Social, cognitive, and computational perspectives)*. Cambridge University Press
Goulah, J. (2017). Climate change and TESOL: Language, literacies, and the creation of eco-ethical consciousness. *TESOL Quarterly*, *51*(1), 90–114. https://doi.org/10.1002/tesq.277
Gouvea, J., & Passmore, C. (2017). Models of versus Models for. *Science & Education*, *26*(1-2), 49–63.
Grapin, S. (2019). Multimodality in the new content standards era: Implications for English learners. *TESOL Quarterly*, *53*(1), 30–55.
Gutiérrez, K., Rymes, B., & Larson, J. (1995). Script, counterscript, and underlife in the classroom: James Brown versus Brown v. Board of Education. *Harvard Educational Review*, *65*(3), 445–472.
Gutiérrez, K. D. (2008). Developing a sociocritical literacy in the third space. *Reading Research Quarterly*, *43*(2), 148–164.
Gutiérrez, K. D., & Jurow, A. S. (2016). Social design experiments: Toward equity by design. *Journal of the Learning Sciences*, *25*(4), 565–598.
Haverly, C., Calabrese Barton, A., Schwarz, C. V., & Braaten, M. (2018). "Making Space": How novice teachers create opportunities for equitable sense-making in elementary science. *Journal of Teacher Education*, *71*(1), 63–79. https://doi.org/10.1177/0022487118800706
Hawkins, M. R. (2018). Transmodalities and transnational encounters: Fostering critical cosmopolitan relations. *Applied Linguistics*, *39*(1), 55–77.
Heller, M., & McElhinny, B. (2017). Chapter 7: On the origins of sociolinguistics: Democracy, development, and emancipation, *Language, capitalism, colonialism: Toward a critical history*. University of Toronto Press.
Hemphill, D., & Blakely, E. (2019). English language learning in Globalized third spaces: From monocultural standardization to hybridized translanguaging. In D. Macedo (Ed.), *Decolonizing foreign language education: The misteaching of English and other colonial languages* (pp. 220–240). Routledge.
Hornberger, N. H., & Link, H. (2012). Translanguaging and transnational literacies in multilingual classrooms: A biliteracy lens. *International Journal of Bilingual Education and Bilingualism*, *15*(3), 261–278.
Hua, Z., Li, W., & Jankowicz-Pytel, D. (2019). Translanguaging and embodied teaching and learning: Lessons from a multilingual karate club in London. *International Journal of Bilingual Education and Bilingualism*, *23*(1), 65–80.
Hudicourt-Barnes, J. (2003). The use of argumentation in Haitian Creole science classrooms. *Harvard Educational Review*, *73*(1), 73–93.
Infante, P., & Licona, P. R. (2018). Translanguaging as pedagogy: Developing learner scientific discursive practices in a bilingual middle school science classroom. *International Journal of Bilingual Education and Bilingualism*, 1–14. https://doi.org/10.1080/13670050.2018.1526885
Jaspers, J. (2018). The Transformative limits of translanguaging. *Language and Communication*, *58*, 1–10. https://doi.org/10.1016/j.langcom.2017.12.001
Jiménez, R. T., David, S., Fagan, K., Risko, V. J., Pacheco, M., Pray, L., & Gonzales, M. (2015). Using translation to drive conceptual development for students becoming literate in English as an additional language. *Research in the Teaching of English*, *49*(3), 248–271.
Karlsson, A., Nygård Larsson, P., & Jakobsson, A. (2019). Multilingual students' use of translanguaging in science classrooms. *International Journal of Science Education*, *41*(15), 2049–2069.
Klopfer, E. (2003). Technologies to support the creation of complex systems models—Using StarLogo software with students. *Biosystems*, *71*(1–2), 111–122.
Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Harvard University Press.
Lee, T., & McCarty, T. (2015). Bilingual-multilingual education of indigenous peoples. In W. Wright, S. Boun, & O. García (Eds.), *Handbook of bilingual and multilingual education* (pp. 409-427). Wiley.
Lehrer, R. (2009). Designing to develop disciplinary dispositions: Modeling natural systems. *American Psychologist*, *64*(8), 759–771.
Lehrer, R., & Schauble, L. (2012). Seeding evolutionary thinking by engaging children in modeling its foundations. *Science Education*, *96*(4), 701–724.
Lehrer, R., & Schauble, L. (2015). The development of scientific thinking. In R. M. Lerner (Ed.), *Handbook of child psychology and developmental science* (pp. 1–44). John Wiley & Sons Ltd.
Lemke, J. L. (2000). Across the scales of time: Artifacts, activities, and meanings in ecosocial systems. *Mind, Culture, and Activity*, *7*(4), 273–290.
Lewis, G., Jones, B., & Baker, C. (2012). Translanguaging: Origins and development from school to street and beyond. *Educational Research and Evaluation*, *18*(7), 641–654.

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Li, W. (2018). Translanguaging as a practical theory of language. *Applied Linguistics*, *39*(1), 9–30.

Licona, P. R., & Kelly, G. J. (2019). Translanguaging in a middle school science classroom: Constructing scientific arguments in English and Spanish. *Cultural Studies of Science Education*, *15*, 485–510.

Lin, A. M., & Wu, Y. (2015). 'May I speak Cantonese?'–Co-constructing a scientific proof in an EFL junior secondary science classroom. *International Journal of Bilingual Education and Bilingualism*, *18*(3), 289–305.

Lippi-Green, R. (2011). Chapters 4: The standard language myth, *English with an accent: Language, ideology and discrimination in the United States*. Routledge.

Machado, E., & Hartman, P. (2019). Translingual writing in a linguistically diverse primary classroom. *Journal of Literacy Research*, *51*(4), 480–503.

MacLeod, M., & Nersessian, N. J. (2013). Coupling simulation and experiment: The bimodal strategy in integrative systems biology. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 573–584.

Makalela, L. (2015). A panoramic view of bilingual education in Sub-Saharan Africa: Reorienting lens for the future. In W. Wright, S. Boun, & O. García (Eds.), *Handbook of bilingual and multilingual education* (pp. 566–577). John Wiley & Sons Ltd.

Makoni, S., & Pennycook, A. (2007). Disinventing and reconstituting languages. Multilingual Matters.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education*, *96*(6), 1071–1105.

Martínez, R. A., Hikida, M., & Durán, L. (2015). Unpacking ideologies of linguistic purism: How dual language teachers make sense of everyday translanguaging. *International Multilingual Research Journal*, *9*(1), 26–42.

Menken, K., & Sánchez, M. T. (2019). Translanguaging in English-only schools: From pedagogy to stance in the disruption of monolingual policies and practices. *TESOL Quarterly*, *53*(3), 741–767.

Milroy, J. (2001). Language ideologies and the consequences of standardization. *Journal of Sociolinguistics*, *5*(4), 530–555.

Moschkovich, J. N. (2015). Academic literacy in mathematics for English learners. *The Journal of Mathematical Behavior*, *40*, 43–62.

National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, core ideas*. National Academies Press.

Nersessian, N. J. (2008). *Creating scientific concepts*. MIT Press.

Nersessian, N. J. (2017). Hybrid devices embodiments of culture in biomedical engineering. In K. Chemla, & E. F. Keller (Eds.), *Cultures without culturalism: The making of scientific knowledge* (pp. 117–144). Duke University Press.

Ochs, E. (2012). Experiencing language. *Anthropological theory*, *12*(2), 142–160.

Oliveira, A. W., Weinburgh, M., McBride, E., Bobowski, T., & Shea, R. (2019). Teaching science to English language learners: Current research and practices in the field of science education, *The handbook of TESOL in K–12* (pp. 277–290). Wiley-Blackwell.

Otheguy, R., García, O., & Reid, W. (2015). Clarifying translanguaging and deconstructing named languages: A perspective from linguistics. *Applied Linguistics Review*, *6*(3), 281–307.

Pacheco, M. B., & Smith, B. E. (2015). Across languages, modes, and identities: Bilingual adolescents' multimodal codemeshing in the literacy classroom. *Bilingual Research Journal*, *38*(3), 292–312.

Parnafes, O., & diSessa, A. (2004). Relations between types of reasoning and computational representations. *International Journal of Computers for Mathematical Learning*, *9*(3), 251–280.

Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. *Journal of the Learning Sciences*, *7*, 429–449.

Pennycook, A., & Makoni, S. (2020). Chapter 5: Decolonizing language in education, *Innovations and challenges in applied linguistics from the Global South*. Routledge.

Perez, W., Vasquez, R., & Buriel, R. (2016). Zapotec, Mixtec, and Purepecha youth: Multilingualism and the marginalization of Indigenous immigrants in the United States. In H. Samy Alim, J. Rickford, & A. Ball (Eds.), *Raciolinguistics: How language shapes our ideas about race* (pp. 255–272). Oxford University Press.

Pickering, A. (1995). *The mangle of practice: Time, agency and science*. University of Chicago Press.

Pierson, A. E., & Brady, C. E. (2020). Expanding opportunities for systems thinking, conceptual learning, and participation through embodied and computational modeling. *Systems*, *8*(4), 48.

Pierson, A. E., Brady, C. E., & Clark, D. B. (2020a). Balancing the environment: Computational models as interactive participants in a STEM classroom. *Journal of Science Education and Technology*, *29*(1), 101–119.

Pierson, A., Brady, C., Clark, D.B., & Sengupta, P. (2020b). Hybrid Modeling in 6th Grade STEM: Seeds of Convergence Research. In M. Gresalfi and I. Horn. (Eds.) *The Interdisciplinarity of the Learning Sciences, 14th International Conference of the Learning Sciences (ICLS) 2020*, (Vol. 1, pp. 19-26). International Society of the Learning Sciences.

Pierson, A. E., Clark, D. B., & Sherard, M. K. (2017). Learning progressions in context: Tensions and insights from a semester-long middle school modeling curriculum. *Science Education*, *101*(6), 1061–1088.

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Poza, L. E. (2018). The language of ciencia: Translanguaging and learning in a bilingual science classroom. *International Journal of Bilingual Education and Bilingualism*, *21*(1), 1–19.

Probyn, M. (2015). Pedagogical translanguaging: Bridging discourses in South African science classrooms. *Language and Education*, *29*(3), 218–234.

Radke, S., Vogel, S., Hoadley, C., & Ma, J. (2020). *Representing percents and personas: Designing syncretic curricula for modeling and statistical reasoning. Proceedings of the International Conference of the Learning Sciences* (Vol. 3, pp. 1365–1372). International Society of the Learning Sciences.

Ranker, J. (2009). Student appropriation of writing lessons through hybrid composing practices: Direct, diffuse, and indirect use of teacher-offered writing tools in an ESL classroom. *Journal of Literacy Research*, *41*, 393–431.

Razfar, A. (2013). Multilingual mathematics: Learning through contested spaces of meaning-making. *International Multilingual Research Journal*, *7*(3), 175–196.

Reigh, E., & Miller, E. (2020). Viewing science as practice: Implications for the language development and inclusion of English Learners, *Proceedings of International Conference of the Learning Sciences* (Vol. 4, pp. 2269–2272). International Society of the Learning Sciences.

Ricento, T. (2013). Language policy, ideology, and attitudes in English-dominant countries, *The Oxford handbook of sociolinguistics*. Oxford University Press.

Rowe, D. W., & Miller, M. E. (2016). Designing for diverse classrooms: Using iPads and digital cameras to compose eBooks with emergent bilingual/biliterate four-year-olds. *Journal of Early Childhood Literacy*, *16*(4), 425–472.

Rowe, L. W. (2018). Say it in your language: supporting translanguaging in multilingual classes. *The Reading Teacher*, *72*(1), 31–38.

Rowe, L. W. (2020). Hey Siri: Exploring the potential for digital tools to support heritage-language use in English-dominant classrooms. *Language Arts*, *97*(6), 363–375.

Sandoval, W. (2014). Conjecture mapping: An approach to systematic educational design research. *Journal of the Learning Sciences*, *23*(1), 18–36.

Seltzer, K. (2020). Translingual writers as mentors in a high school "English" classroom, *Plurilingual Pedagogies* (pp. 185–204). Springer.

Seltzer, K., & de los Ríos, C. V. (2018). Translating theory to practice: Exploring teachers' raciolinguistic literacies in secondary English classrooms. *English Education*, *51*(1), 49–79.

Sengupta, P., Dickes, A., & Farris, A. V. (2021). *Voicing code in STEM: A dialogical imagination*. MIT Press.

Sengupta, P., & Wilensky, U. (2009). Learning electricity with NIELS: Thinking with electrons and thinking in levels. *International Journal of Computers for Mathematical Learning*, *14*(1), 21–50.

Sherris, A., & Adami, E. (Eds.). (2019). Making signs; Translanguaging ethnographies, *Exploring urban, rural and educational space*. Multilingual matters.

Shin, S. (2017). *Bilingualism in schools and society: Language, identity, and policy* (2nd ed.). Routledge

Smith, B. E., Pacheco, M. B., & de Almeida, C. R. (2017). Multimodal codemeshing: Bilingual adolescents' processes composing across modes and languages. *Journal of Second Language Writing*, *36*, 6–22.

Smith, B. E., Pacheco, M. B., & Khorosheva, M. (2020). Emergent bilingual students and digital multimodal composition: A systematic review of research in secondary classrooms. *Reading Research Quarterly*, *56*(1), 33–52.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research* (Vol. 15). Newbury Park, CA: Sage.

Suárez, E., Tzou, C., Bang, M., Meixi, Roque, R., Pinkard, N., & Martin, C. K. (2018). Designing for axiological innovation within family-centered learning environments, *Rethinking learning in the digital age: Making the learning sciences count* (Vol. II, pp. 1187–1194). ISLS.

Turner, M., & Lin, A. M. (2020). Translanguaging and named languages: Productive tension and desire. *International Journal of Bilingual Education and Bilingualism*, *23*(4), 423–433.

Viesca, K. M., & Teemant, A. (2019). Preparing content teachers to work with multilingual students, *The handbook of TESOL in K–12* (pp. 371–385). John Wiley & Sons Ltd.

Vogel, S., Ascenzi-Moreno, L., & García, O. (2018). *An expanded view of translanguaging: Leveraging the dynamic interactions between a young multilingual writer and machine translation software*. CUNY Academic Works.

Vogel, S., Hoadley, C., Ascenzi-Moreno, L., & Menken, K. (2019). The Role of Translanguaging in Computational Literacies: Documenting Middle School Bilinguals' Practices in Computer Science Integrated Units. *Proceedings of the 50th ACM Technical Symposium on Computer Science Education* (pp. 1164–1170). Association for Computing Machinery, Inc. https://doi.org/10.1145/3287324.3287368

Wilensky, U., & Stroup, W. (1999). Learning through participatory simulations: Network-based design for systems learning in classrooms, *Computer-supported collaborative learning*. Stanford University.

Williams, C. (1994). *Arfarniad o ddulliau dysgu ac addysgu yng nghyd-destun addysg uwchradd ddwyieithog* (Doctoral dissertation). Wales, UK, University of Bangor.

1098237x, 2021, 4, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sce.21622 by New York University, Wiley Online Library on [24/10/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Williams, M. (2020). Fifth graders' use of gesture and models when translanguaging during a content and language integrated science class in Hong Kong. *International Journal of Bilingual Education and Bilingualism*, 1–20. https://doi.org/10.1080/13670050.2020.1754752
Wilson, W., & Kamana, K. (2009). Indigenous youth bilingualism from a Hawaiian activist perspective. *Journal of Language, Identity, & Education*, *8*, 369–375.
Wu, S. C., Silveus, A., Vasquez, S., Biffi, D., Silva, C., & Weinburgh, M. (2019). Supporting ELLs' use of hybrid language and argumentation during science instruction. *Journal of Science Teacher Education*, *30*(1), 24-43.
Yin, R. K. (2014). *Case study research: Design and methods (applied social research methods)*. Sage Publications.
Zapata, A., & Laman, T. T. (2016). I write to show how beautiful my languages are: Translingual writing instruction in English-dominant classrooms. *Language Arts*, *93*(5), 366–378.
Zheng, B., Warschauer, M., Hwang, J. K., & Collins, P. (2014). Laptop use, interactive science software, and science learning among at-risk students. *Journal of Science Education and Technology*, *23*(4), 591–603. https://doi.org/10.1007/s10956-014-9489-5

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APPENDIX A: INTERVIEW PROTOCOL

1. Show a picture of each of the students' models: plant investigation, biosphere plan, biosphere model, food web, embodied model, computational model. For each model, ask:
   a. Can you tell me about making this model?
   b. What does this model show?
   c. What languages did you use in this model?
2. Are any of the models related to each other? Why or why not?
3. Which of the models were the most interesting or helpful to you?
4. Which of the models were the least interesting or helpful to you?
5. Did you use different languages in your models?
   a. If yes: Does using different languages change how you think?
   b. If yes: Can you tell me about a time when that happened?
6. In your science class, we used a computational model about zebra mussels. But we didn't build that one—it was already built.
   a. If you think about the scientists that built that model, what kind of information do you think they needed to build it?
   b. How do you think they get that information?
   c. Do you think those scientists use other models to understand zebra mussels?
      i. If yes: Which types of models? How would they use them?
7. Is there anything we should definitely keep or definitely change about these projects for next quarter?

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