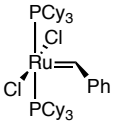
Chapter 3
Chemoselective Conjugated Diene Cross-Metathesis

Introduction

As discussed in the previous chapter, olefin cross-metathesis (CM) appears to be a straightforward, reliable method for the intermolecular coupling of two olefins. In reality, complications often arise due to the similar reactivities of simple olefins, especially when a highly active catalyst (such as **2**, **3**, or **4**) is used.[1] The formation of undesired homocoupled products can be diminished by increasing the steric bulk around the alkene or by reducing its electron density. Substitution in the allylic position causes products to be enriched in the desired heterocoupled olefin, but alkenes with substitution directly on the double bond (i.e., 1,1-disubstituted olefins) do not react efficiently in CM reactions with **2** or **3**, and yields are typically reduced relative to monosubstituted terminal olefins.[2] The low yields obtained for trisubstituted vinyl boronate formation presented in chapter 2 support this generalization.



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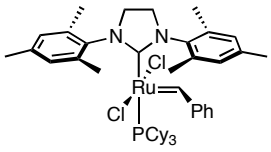

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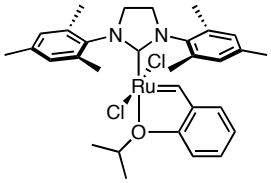

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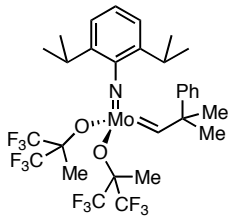

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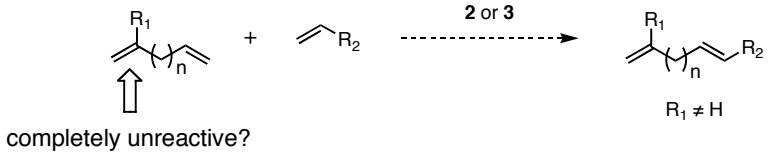
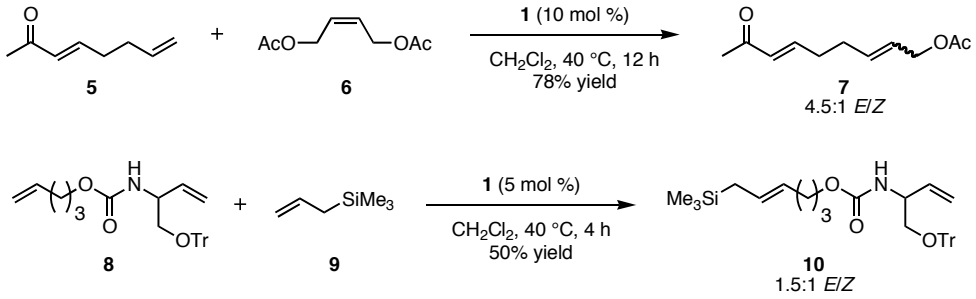
Although trisubstituted vinyl boronate synthesis by CM was only moderately successful, the lack of reactivity of catalyst **2** toward 1,1-disubstituted olefins suggested it could be used in chemoselective CM reactions. If a substrate containing both a monosubstituted terminal olefin and a 1,1-disubstituted olefin was used in a CM reaction,

catalyst **2** should react preferentially with the monosubstituted alkene (Scheme 3.1). A reaction of this type could have great synthetic potential.

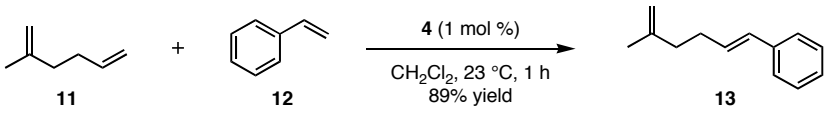


Scheme 3.1. Proposed chemoselective CM using a ruthenium catalyst.

Chemoselective CM had been previously achieved with catalysts **1** and **4** prior to this work. For example, catalyst **1** does not react efficiently with electron-poor olefins or with allylic amines, so it was used to selectivity react with unhindered terminal alkenes in the reactions illustrated in Scheme 3.2. In the upper reaction, the alkene in conjugation with the ketone does not react;[1a] in the lower reaction, the less hindered terminal olefin undergoes CM selectively.[3] Alkenes that are 1,1-disubstituted do not react with catalyst **4**, so a selective CM was achieved using **11** and styrene (**12**) (Scheme 3.3).[4] The latter reaction, which used a molybdenum catalyst instead of a ruthenium catalyst, is almost identical to the proposed chemoselective CM.

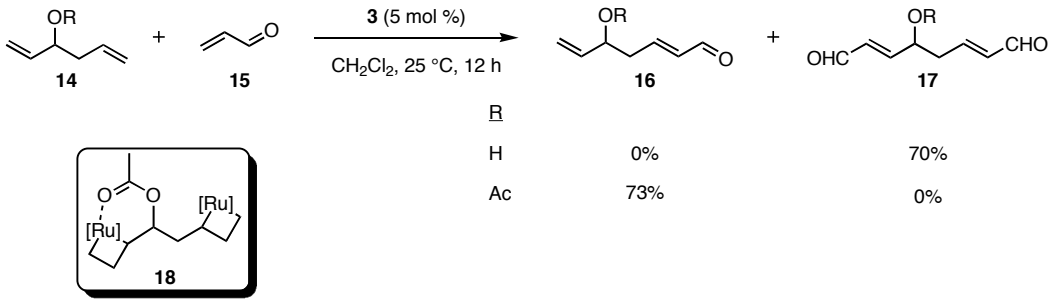


Scheme 3.2. Chemoselective CM using catalyst **1**.



Scheme 3.3. Chemoselective CM using catalyst **4**.

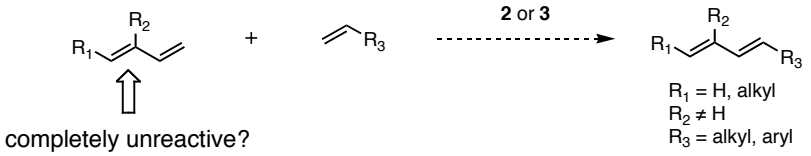
The reactions shown in Schemes 3.2 and 3.3 were successful because a catalyst was chosen that was known to be unreactive toward one of the olefins. Catalyst **1** was a reliable choice for chemoselective CM due to its low reactivity. On the other hand, catalysts **2** and **3** are significantly more reactive than **1**, and chemoselective CM is expected to be more challenging. When the research described in the current chapter began, there was only one report on chemoselective CM using N-heterocyclic carbene (NHC)-containing ruthenium metathesis catalysts.[5,6] Two olefins were present in the substrate (**14**): one had an alcohol or acetate in the allylic position, and the other alkene had an alcohol or acetate in the homoallylic position. When the alcohol was unprotected, CM occurred at both olefins using catalyst **3** (Scheme 3.4). If the alcohol was protected with an acetate group, CM occurred selectively at the homoallylic olefin. It was proposed that the deactivation of the allylic alkene was due to either the electron-withdrawing capability of the acetate group or to the formation of a stabilized, non-reactive complex (**18**). Steric hindrance was not thought to play a role in the selectivity.



Scheme 3.4. Chemoselective CM using a highly active ruthenium catalyst.

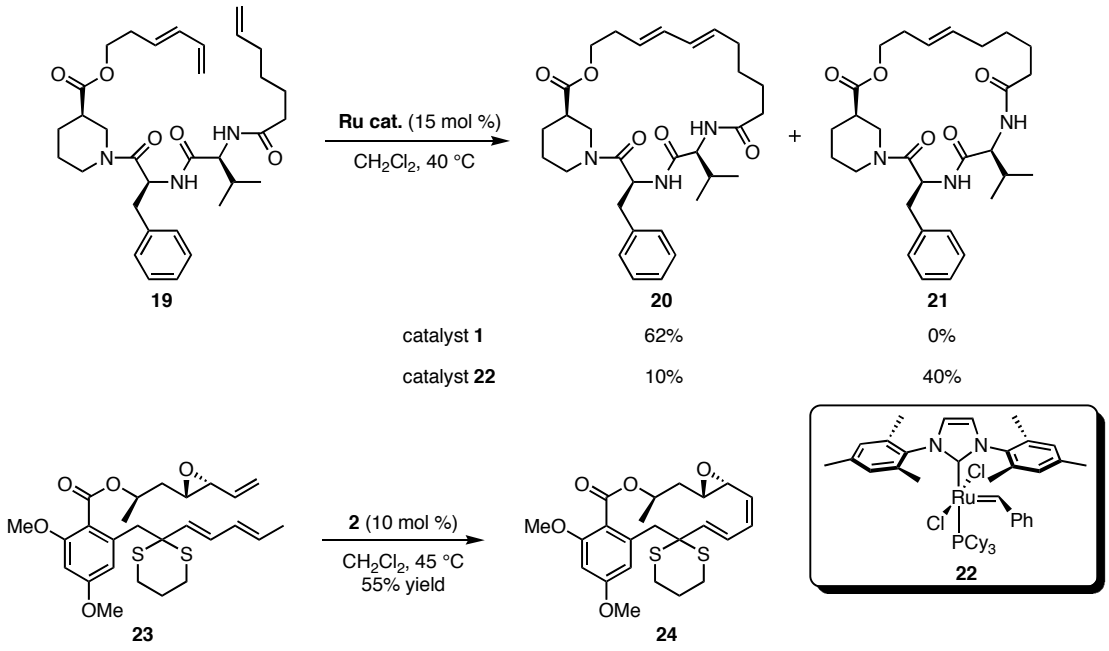
It is obvious from the examples above that chemoselective CM is a useful tool in accessing certain α,ω-dienes. Conjugated dienes, which are a category of substrates that fit the reaction proposed in Scheme 3.1, are found in natural products and are useful synthetic intermediates. Chemoselective CM could be used to form substituted

conjugated dienes as long as there is a substituent in an appropriate position to decrease the reactivity of one of the olefins (Scheme 3.5). Because ruthenium-catalyzed CM is mild and experimentally simple, chemoselective conjugated diene CM would be a synthetically valuable reaction.



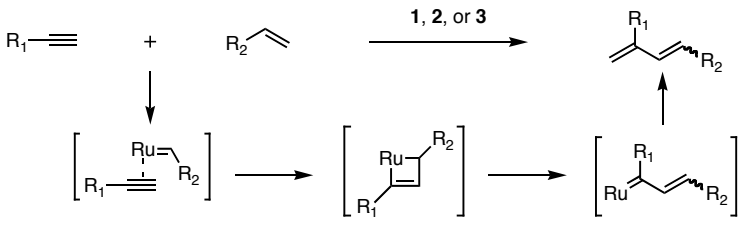
Scheme 3.5. Proposed chemoselective CM reaction of 2-substituted and 1,2-disubstituted 1,3-butadienes.

Conjugated diene olefin metathesis had been used in several natural product syntheses prior to the start of the work described here. In all cases, a macrocycle was formed using conjugated diene ring-closing metathesis (RCM) (Scheme 3.6). The Nolan group used the less active catalyst **1** to couple the two terminal olefins of substrate **19**; the more active compound **22** catalyzed metathesis at both olefins of the conjugated diene.[7] Danishefsky used catalyst **2** to form **24**, an advanced intermediate in the synthesis of radicicol and monocillin.[8] Because of the steric bulk around the internal alkene of the conjugated diene, olefin metathesis occurred exclusively between the two terminal olefins in the latter example. 1,1-Disubstituted alkenes were not present in any of these reactions.



Scheme 3.6. Conjugated diene RCM in natural product synthesis.

Enyne metathesis is another approach to the synthesis of conjugated dienes using olefin metathesis catalysts (Scheme 3.7).[9] Intramolecular enyne metathesis has been widely used to access natural products and diverse libraries of compounds. Intermolecular enyne metathesis (enyne CM) has been used less frequently than the intramolecular reaction. 2-Substituted conjugated dienes can be made using enyne CM with an alkyne and ethylene. When higher alkenes are used, products similar to those illustrated in Scheme 3.5 are formed. Unfortunately, catalyst loadings greater than 5%, low *E*/*Z* ratios of the products, and a large excess of the starting alkene decrease the synthetic practicality of this reaction.

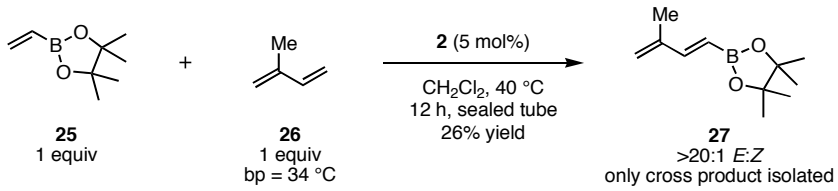


Scheme 3.7. Enyne CM and proposed mechanism.

Although a lot work had been done focusing on the synthesis of conjugated dienes using olefin metathesis, there were no examples where a chemoselective CM reaction was used to form conjugated dienes as shown in Scheme 3.5. Conjugated dienes are used as synthetic intermediates and are present in many natural products. Additionally, olefin metathesis is a mild, catalytic synthetic method that has found widespread use in organic chemistry. For these reasons, chemoselective conjugate diene CM was explored.

Results and Discussion[10]

The first reaction that was attempted was a CM between vinyl pinacol boronate (**25**) and isoprene (**26**) (Scheme 3.8). Isoprene has a boiling point of 34 °C, which is below the typical reaction temperature for vinyl boronate cross-metathesis, so the reaction was performed in a sealed tube. Although **27** was formed in only 26% yield, it was the only cross-metathesis product found in the reaction mixture. There was no product resulting from a reaction at the 1,1-disubstituted alkene, and only the *E*-isomer was formed.

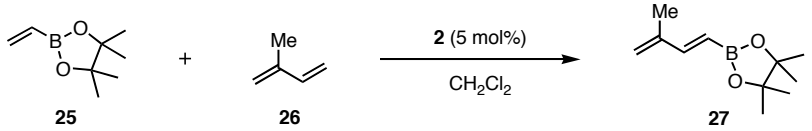


Scheme 3.8. Chemoselective conjugated diene CM to form a single product.

A variety of other reaction conditions were employed in the CM between **25** and **26**, but the yield was never higher than 48% (Table 3.1). One of the major driving forces for CM is the release of ethylene, and in a sealed tube, the ethylene remains present. Performing the reaction in an open flask did not increase the yield, even when isoprene

(**26**) was used as the solvent. The reaction was run under an atmosphere of ethylene to see if that would improve the yield, but it appeared to not affect the reaction at all.[11] In all of the conditions screened, the only product formed was **27**.

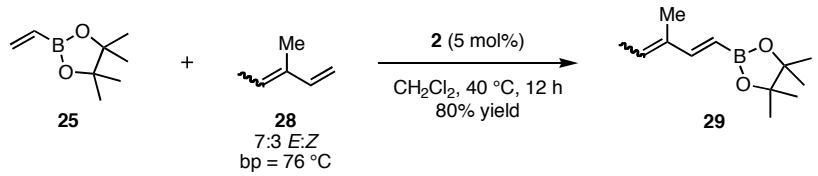
Table 3.1. CM of vinyl pinacol boronate and isoprene using catalyst **2**.



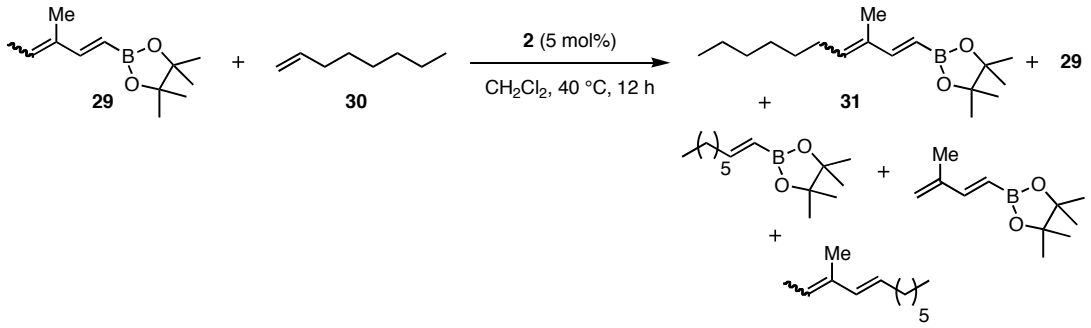
25 + **26** → **27**

Entry	25:26 (Equiv)	Type of Flask	Temp (°C)	Yield (%)
1	1:1	Sealed tube	40	26
2	1:2	Flask with condenser	32	34
3	1:4	Flask with condenser	40	<5
4	1:31 (solvent)	Flask with condenser	30	<5
5	1:2	Sealed tube	40	48
6	2:1	Sealed tube	40	22
7	1:1 (ethylene atm)	Sealed tube	40	26

The low boiling point of isoprene may have prevented high yields, so a higher boiling conjugated diene was used. Vinyl boronate **25** underwent chemoselective and diastereoselective CM with commercially available 3-methyl-1,3-pentadiene (**28**) to afford **29** in 80% isolated yield (Scheme 3.9). Compound **28** was used as a 7:3 *E*/*Z* mixture of isomers, and both isomers reacted. Only the *E*-isomer of the alkene formed in the CM reaction was observed. It was thought that once the vinyl boronate was crossed onto the diene, the new vinyl boronate olefin would be unreactive to further metathesis. Compound **29** was exposed to 1-octene (**30**) and more **2**, with the aim of producing **31**, which would come from a CM with the more substituted olefin of the diene (Scheme 3.10). Unfortunately a mixture of products, identified by ^{1}H NMR spectroscopy and GC-MS, was formed, and **31** was only present in <5%, indicating that the boronate-substituted alkene could still react.

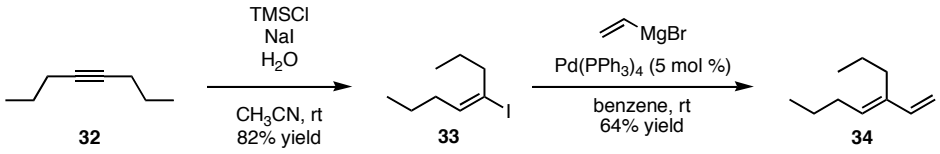


Scheme 3.9. CM of a 1,2-disubstituted 1,3-butadiene.



Scheme 3.10. Attempt to further functionalize **29** with CM.

Because the reaction with **28** was successful, another 1,2-disubstituted conjugated diene was made (Scheme 3.11). 4-Octyne (**32**) was reacted with an acetonitrile solution of HI generated in situ, and vinyl iodide **33** was isolated in 82% yield as a single stereoisomer.[12] A palladium-catalyzed Kumada coupling was used to form the conjugated diene **34** in 64% yield, also as a single stereoisomer.[13] This compound was stable for months in the refrigerator.

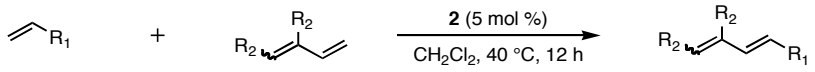


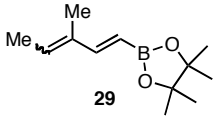
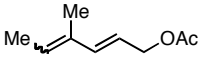
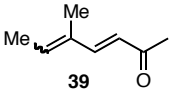
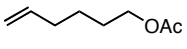
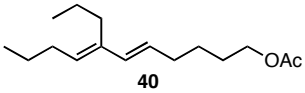
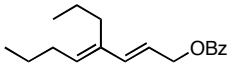
Scheme 3.11. Synthesis of substituted conjugated diene **34**.

With 1,2-disubstituted-1,3-butadienes **28** and **34** in hand, reactions with a number of different alkenes were explored (Table 3.2). 1,4-Diacetoxy-*cis*-2-butene (**6**) reacted with diene **28** in good yield to form an allyl-substituted conjugated diene (entry 2). Methyl vinyl ketone, an electron-poor olefin, also reacted with **28** to form a highly

conjugated molecule (entry 3). Diene **34** reacted similarly to **28**, and the CM reactions afforded products that were isolated in >75% yield. Only the *E*-isomers of all products were formed.

Table 3.2. CM reactions of 1,2-disubstituted 1,3-butadienes.

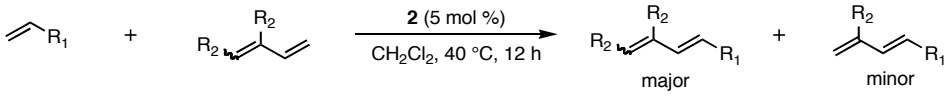


Entry	Alkene (equiv)	Diene[a]	Product	Yield (%)[b]	CH_2-Terminated Product (%)
1	**25** (1 equiv)	**28**	 **29**	80	10
2	 **6** (2 equiv)	**28**	 **38**	82	9
3	 **35** (1 equiv)	**28**	 **39**	70	7
4[c]	 **36** (4 equiv)	**34**	 **40**	77	12
5[d]	 **37** (2 equiv)	**34**	 **41**	79	0

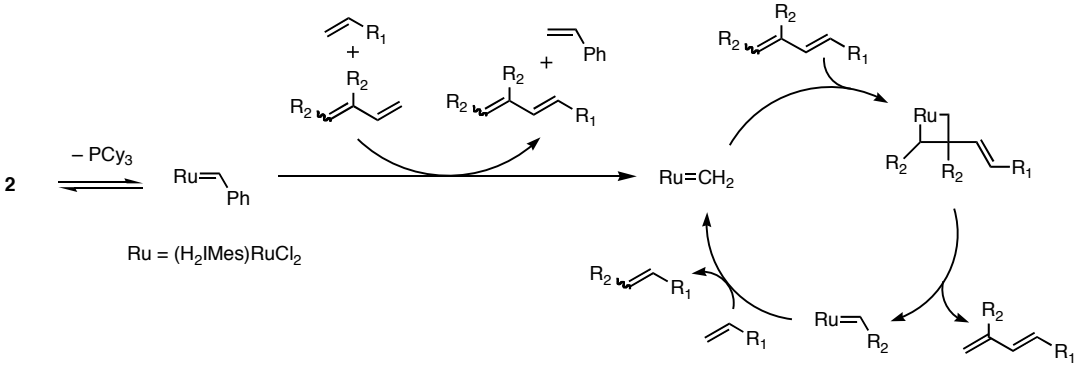
[a] Diene **28** was used as a 70:30 *E*/*Z* mixture. [b] Only the *E*-isomer of the products was observed in all cases; when diene **28** was used, both isomers reacted. [c] Product not separated from unreacted **36**. [d] Product not separated from allyl benzoate formed in reaction.

In addition to the desired products that were isolated in the reactions shown in Table 3.2, a minor impurity was often observed in the ^{1}H NMR spectrum. Ultimately it was determined that the impurity was the desired CM product where the alkyl group in the 1-position had been replaced with an H atom (Scheme 3.12). The far right column in Table 3.2 shows the amount of CH_2-terminated product that was present in each reaction. This product must originate from the formation of a ruthenium methylidene, which reacts with the more substituted olefin of the conjugated diene (Scheme 3.13). CM between the

methylidene and the hindered alkene of the diene could occur before or after the less-hindered olefin reacts with the cross partner. The amount of impurity is higher when an alkene that homocouples readily (i.e., **36**) is used, presumably because excess ethylene is formed. None of the product derived from CM between the alkene and the trisubstituted olefin of the conjugated diene was ever observed.



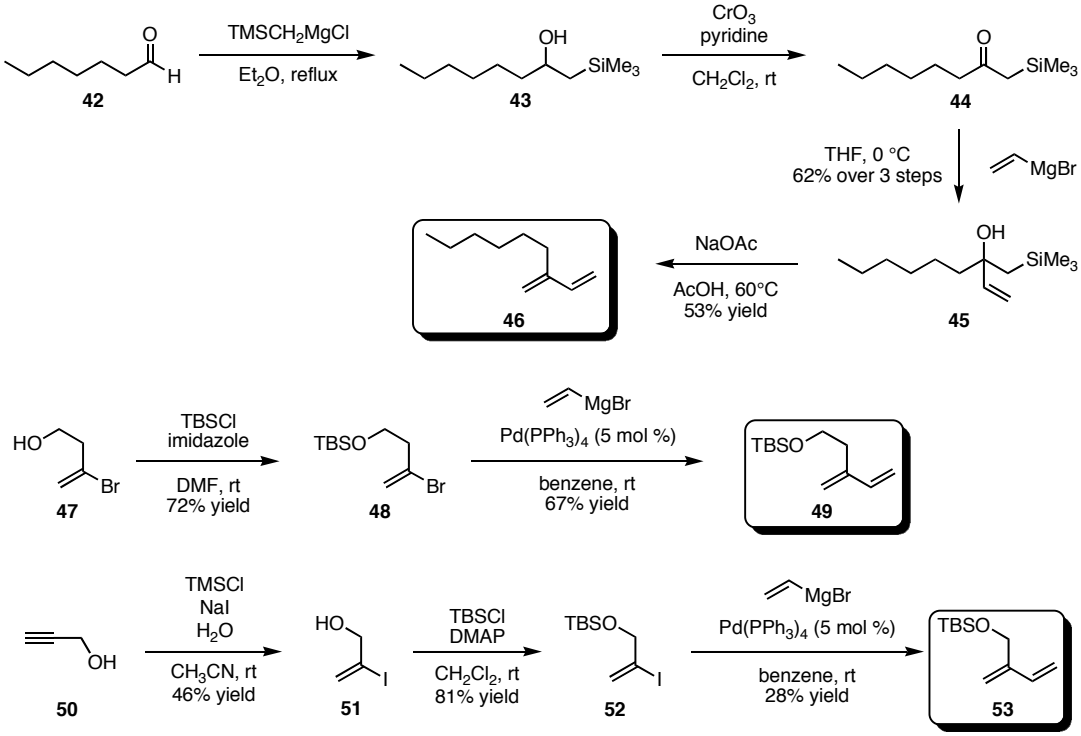
Scheme 3.12. Conjugated diene CM and the CH_2-terminated impurity.



Scheme 3.13. A proposed pathway leading to CH_2-terminated impurity.

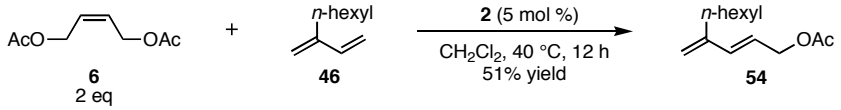
Conjugated diene CM was a success with 1,2-disubstituted 1,3-butadienes. The reactions were chemoselective with respect to the alkene cross partner, and only the *E*-isomer was isolated in all cases. But the question still remained as to whether the reaction would be successful with 2-substituted 1,3-butadienes. CM with isoprene was only moderately successful, and the low yields were attributed to the low boiling point of the diene. Therefore, 2-substituted 1,3-butadienes with higher boiling points were synthesized and used in CM. The syntheses of three conjugated dienes used in this study are shown in Scheme 3.14. Diene **46** was made in a four-step synthesis that was a modification of a known procedure.[14] The Collins oxidation to form **44** was very rapid,

and the α-silyl ketone was not stable under the reaction conditions, so the reaction mixture was filtered through silica within 1 minute after addition of **43**. Purification was not needed until after the third step. Silyl ether **48** reacted with vinyl magnesium bromide in the presence of a palladium catalyst to afford diene **49**.[13] Compound **53** was synthesized in a sequence similar to that of **49**. The Kumada coupling was low yielding, possibly due to elimination of the vinyl iodide or magnesium-iodide exchange.



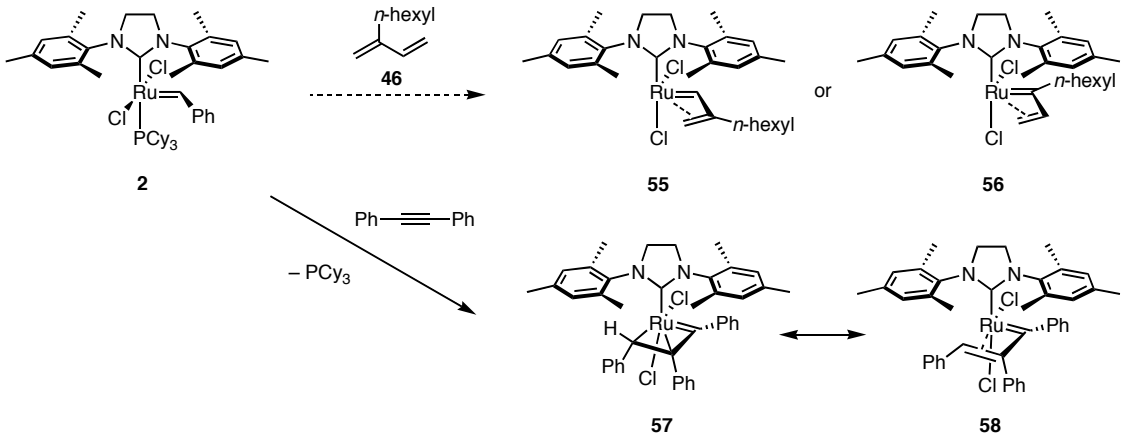
Scheme 3.14. Synthesis of three conjugated dienes.

The first CM reaction with a 2-substituted 1,3-butadiene that was explored was between **46** and **6** (Scheme 3.15). When the same conditions used for the other conjugated diene CM reactions were employed, the desired product was isolated in 51% yield. The reaction was completely chemoselective, and only the *E*-isomer was produced, but there was room for improvement regarding the yield.



Scheme 3.15. CM with **46** using standard conditions.

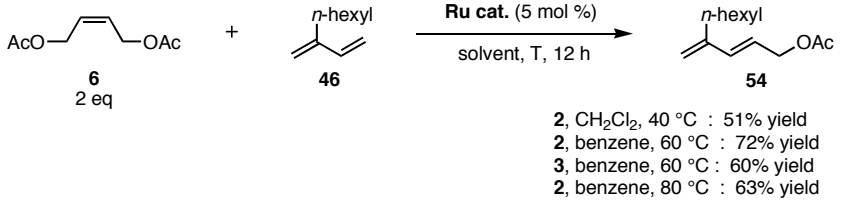
Unreacted **46** was present at the end of the reaction, which suggested that the catalyst may have been shut down before the CM was complete. If the conjugated diene reacted with the catalyst to form a vinyl alkylidene, intramolecular coordination of the alkene may have formed a stabilized, less active metathesis catalyst (Scheme 3.16, compounds **55** and **56**). A ruthenium complex with a similar structure has been reported.[15] The reaction of diphenylacetylene with **2** forms a metathesis-inactive ruthenium complex (**57**) that resembles a vinyl alkylidene acting as a bidentate or tridentate ligand. Additionally, yields for some enyne metathesis reactions can be drastically increased by performing the reaction under an atmosphere of ethylene, which has been proposed to break up coordination of the vinyl alkylidene formed during the catalytic cycle (see Scheme 3.7).[16]



Scheme 3.16. Stabilized intermediates potentially hindering conjugated diene CM reactions.

When the solvent was changed to benzene and the temperature of the CM reaction was increased to 60 °C, the desired conjugated diene product was formed in 72% yield

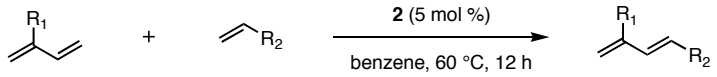
(Scheme 3.17). The elevated temperature may have weakened a ruthenium–alkene dative bond and allowed the stabilized ruthenium intermediate to reenter the catalytic cycle. Increasing the temperature to 80 °C resulted in a lower yield, potentially due to catalyst decomposition. Catalyst **2** afforded the conjugated diene in a higher yield than **3** under the same conditions. The increase in temperature did not affect the chemo- or stereoselectivity of the CM reaction; only one product was formed.

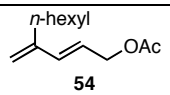
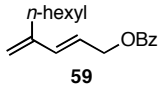
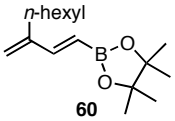
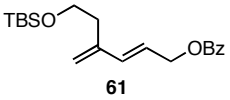
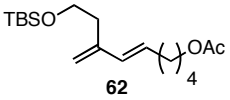
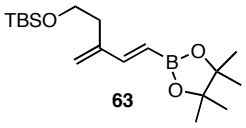
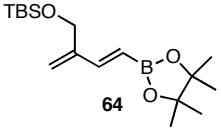
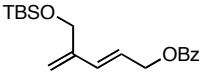


Scheme 3.17. Solvent and temperature effects in conjugated diene CM.

Using the modified reaction conditions, various 2-substituted 1,3-butadienes reacted with functionalized olefins to form the desired dienes in good yields with high chemo- and diastereoselectivity (Table 3.3). Only the *E*-isomer was observed in all of the reactions. Vinyl boronate **25** reacted cleanly with dienes **46** and **49**, as long as the reaction was stopped after 2 h (entries 3 and 6). Longer reaction times did not increase the yield, and an unidentified, inseparable impurity was formed. When **53** and **25** were reacted, the impurity was present even after 2 h (entry 7). Dienes **46** and **49** behaved similarly to each other in the CM reactions; yields were typically 70%–75%, and the reactions were clean. The yields decreased in reactions where the silyl ether functionality was separated from the diene by only one methylene (**53**). When **53** was used as a tetrahydropyranyl (THP)-protected alcohol, the desired dienes were formed in <40% yield. Unreacted diene was present at the end all of the CM reactions with 2-substituted 1,3-butadienes, but longer reaction times did not increase yields.

Table 3.3. CM with 2-substituted 1,3-butadienes.



Entry	Alkene (equiv)	Diene	Product[a]	Yield (%)[b]
1	**6** (2)	**46**	 **54**	72 (81)
2[c]	**37** (2)	**46**	 **59**	73
3[d]	**25** (2)	**46**	 **60**	73
4	**37** (2)	**49**	 **61**	70
5	**36** (4)	**49**	 **62**	75
6[d]	**25** (2)	**49**	 **63**	69
7[d,e]	**25** (2)	**53**	 **64**	~40
8	**37** (2)	**53**	 **65**	63

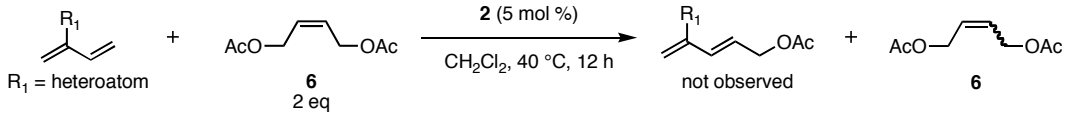
[a] Only the *E*-isomer of the product was observed. [b] Yield in parentheses refers to reaction with 10 mol % **2**. [c] Product not separated from allyl benzoate formed in reaction. [d] Reaction stopped after 2 h. [e] Unidentified impurities present in isolated product.

The reactions in Table 3.3 all required excess alkene to achieve good yields. Attempts to homocouple the 2-substituted 1,3-conjugated dienes were unsuccessful, which suggested that the CM reaction should be selective for the desired heterocoupled product.[17] If that were the case, only one or two equivalents of alkene should have been needed to access the desired diene in high yield, but 2–4 equivalents of the alkene must be used (2 equivalents of **6** and **37** are the same as 4 equivalents of allyl acetate and allyl

benzoate, respectively). The need for excess cross partner highlights the importance of not allowing the diene to react with the catalyst to form a vinyl alkylidene species. The higher concentration of reactive olefin can reduce the interaction between the catalyst and the diene.

All of the 2-substituted 1,3-butadienes in Table 3.3 have a carbon atom bound to the conjugated diene. Dienes with heteroatoms in the 2-position are important synthetic intermediates, so CM with this class of compounds was explored. Chloroprene (**66**), the trimethylsilyl enol ether of methyl vinyl ketone (**67**), and the triisopropylsilyl enol ether of methyl vinyl ketone (**68**) were reacted with 1,4-diacetoxy-*cis*-2-butene (**6**) under typical CM conditions (Table 3.4). None of the desired product was detected in any reaction, even when they were run at 60 °C in benzene.

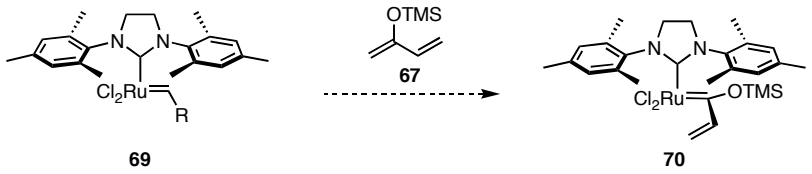
Table 3.4. Attempted CM reactions with heteroatom-substituted conjugated dienes.



Diene	*E*:*Z* ratio of 6
No diene	12 : 1
 **66**	1 : 2.7
 **67**	1 : 1.5
 **68**	2.8 : 1

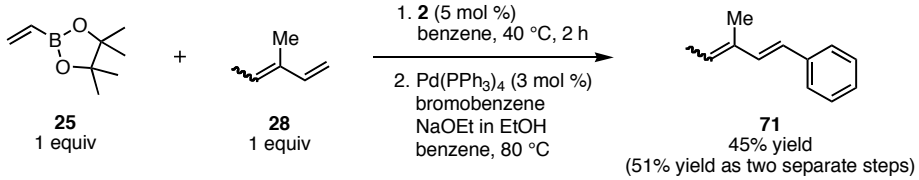
Insight into the fate of these reactions could be obtained by monitoring the amount of **6** that was isomerized. In the absence of another alkene, **6** was isomerized by **2** to a 12:1 *E*:*Z* mixture after 12 h at 40 °C in CH_2Cl_2. In the presence of dienes with

heteroatom substitution in the 2-position, **6** never completely isomerized, indicating catalyst decomposition. As the heteroatom substituent decreased in size, the amount of *E*-isomer formed also decreased. These data are consistent with the formation of a Fischer carbene by the reaction of a catalytically active ruthenium alkylidene with the more hindered olefin of the conjugated diene (Scheme 3.18). Ruthenium Fischer carbenes typically show greatly reduced metathesis activity, so any formed during this reaction exit the catalytic cycle.[18]



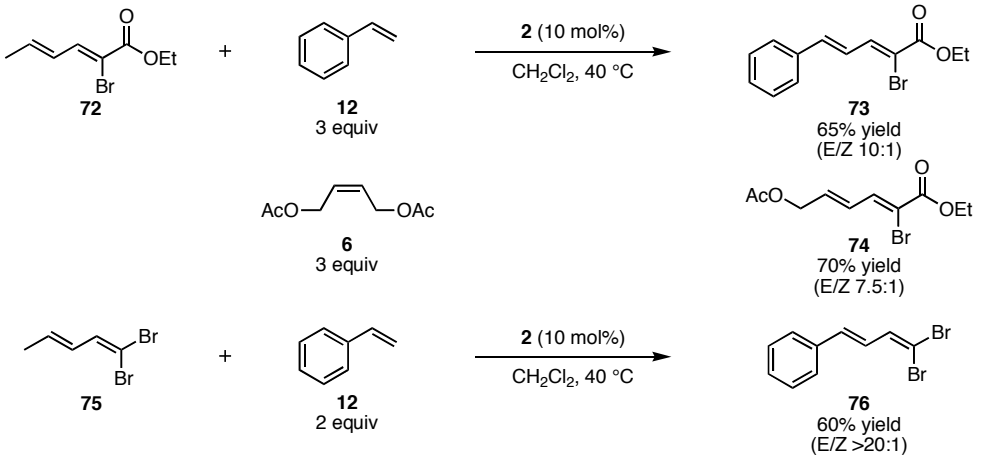
Scheme 3.18. Fischer carbene formed by **69** reacting with the silyl enol ether of **67**.

The conjugated dienes generated over the course of this study have the potential to be further functionalized, even without isolation. For example, dienes synthesized by enyne metathesis reactions have undergone [4 + 2]-cycloadditions without purification.[19] One of the unique features of this work is the formation of conjugated vinyl boronates, which are versatile functional groups. As illustrated in Scheme 3.19, a one-pot, chemoselective, conjugate diene CM/Suzuki coupling was successfully executed. The yield of this unoptimized reaction was similar to the two-step procedure, but no purification was needed after CM.



Scheme 3.19. One-pot conjugate diene CM/Suzuki coupling.

In addition to the 2-substituted and 1,2-disubstituted 1,3-butadienes discussed in this chapter, other conjugated diene CM has been explored in our lab by Dr. Jon Efskind.[10] Although the details of that work are beyond the scope of this chapter, a few sentences regarding it are warranted. It was thought that a combination of steric hindrance and electronic deactivation would render the trisubstituted alkenes of **72** and **75** unreactive to CM with catalyst **2**. This theory was tested, and CM occurred exclusively at the 1,2-disubstituted olefins (Scheme 3.20). The yields are only slightly reduced relative to most of the reactions discussed above, and the products have a variety of different functional group handles, making the products useful synthetic intermediates.



Scheme 3.20. Conjugated diene CM with 1,1-disubstituted 1,3-butadienes.

Conclusion

Conjugated dienes are important in organic chemistry as both constituents of natural products and synthetic intermediates. Therefore, the development of methods by which substituted conjugated dienes can be generated is crucial. Chemoselective cross-metathesis (CM) was successfully used to couple 2-substituted and 1,2-disubstituted 1,3-butadienes to a variety of functionalized alkenes. This technique took advantage of the

lack of reactivity between ruthenium olefin metathesis catalyst **2** and 1,1-disubstituted alkenes. Many of the conjugated dienes formed using this method contain functional groups that can undergo further manipulation, and it was discovered that a one-pot CM/Suzuki coupling reaction was possible. The simplicity of use and functional group tolerance of ruthenium metathesis catalysts, as well as the high chemo- and diastereoselectivity with which these transformations occurred, make this an attractive method for synthesizing functionalized conjugated dienes.

Experimental

General Experimental. NMR spectra were recorded on an Oxford 300 MHz NMR spectrometer running Varian VNMR software. Chemical shifts are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) with reference to internal solvent. Multiplicities are abbreviated as follows: singlet (s), doublet (d), triplet (t), quartet (q), quintet (quint), sextet (sext), multiplet (m), and broad (br). Spectroscopic data are provided for the major olefin isomer. For all vinylboronates reported the ^{13}C peak of the α-carbon is not observed due to the large quadrupolar effect of the attached boron nucleus. E/Z ratios given for the products indicate the ratios of the C=C bond formed in cross-metathesis and were determined from coupling constants of vinylic protons in the ^{1}H NMR spectrum.

Analytical thin-layer chromatography (TLC) was performed using silica gel 60 F254 precoated plates (0.25 mm thickness) with a fluorescent indicator. Visualization was performed with standard potassium permanganate stains or UV light. Flash column chromatography was performed using silica gel 60 (230–400 mesh). All glassware was

either oven dried or flame dried, and reactions were done under an atmosphere of argon. All commercial chemicals were used as obtained except 1,4-diacetoxy-*cis*-2-butene (**6**), which was distilled from CaH_2, and heptanal (**42**), which was distilled. 3-Methyl-1,3-pentadiene (**28**) was received (Aldrich) as a 70:30 mixture of E/Z isomers, and both isomers underwent cross-metathesis in the examples below (NMR spectral data are given for both isomers whenever they could be determined). Benzene, methylene chloride, diethyl ether, and THF were dried by passage through solvent columns containing activated alumina.

(*E*)-4,4,5,5-Tetramethyl-2-(3-methylbuta-1,3-dienyl)-1,3,2-dioxaborolane (27). To a solution of **2** (28 mg, 0.032 mmol) in 2 mL of CH_2Cl_2 in a pressure vessel was added isoprene (**26**) (130 μL, 89 mg, 1.3 mmol) and **25** (111 μL, 100 mg, 0.65 mmol). The vessel was sealed, and the reaction solution stirred at 40 °C. After 12 h at 40 °C, the solution was condensed, and the remaining residue was purified by flash chromatography (4% ethyl acetate in hexanes) to afford 49 mg of a 4:3 **27**:**25** mixture (31 mg of **27**, 48% yield). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.11 (d, J = 18.1 Hz, 1H), 5.56 (d, J = 18.1 Hz, 1H), 5.16 (s, 2H), 1.86 (s, 3H), 1.29 (s, 12H).

(*E*)-4-Iodooct-4-ene (33).[12] To a solution of sodium iodide (1.63 g, 10.9 mmol) in 20 mL of acetonitrile was added trimethylsilyl chloride (1.4 mL, 1.2 g, 11 mmol), followed by water (98 μL, 98 mg, 5.4 mmol). After 10 min at rt, 4-octyne (**32**) (1.3 mL, 1.0 g, 9.1 mmol) was added. After 1 h at rt, the solution was diluted with 25 mL of water and was extracted with Et_2O (3 × 40 mL). The combined organic layers were washed with

saturated aqueous $Na_2S_2O_3$ (2 × 40 mL), 40 mL of brine, dried over $MgSO_4$, and evaporated to an oil. Purification by flash chromatography (100% hexanes) afforded 1.77 g (82% yield) of **33** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 5.47 (tt, J = 6.9, 1.1 Hz, 1H), 2.44 (tq, J = 7.4, 1.1 Hz, 2H), 2.06–2.14 (m, 2H), 1.54 (sext, J = 7.4 Hz, 2H), 1.43 (sext, J = 7.4 Hz, 2H), 0.94 (t, J = 7.4 Hz, 3H), 0.88 (t, J = 7.4 Hz, 3H).

(*E*)-4-Vinyloct-4-ene (34).[13] To a solution of $Pd(PPh_3)_4$ (340 mg, 0.29 mmol) in 30 mL benzene at rt was added **33** (1.4 g, 5.9 mmol) and vinylmagnesium bromide (1M in THF, 11.8 mL, 11.8 mmol). After 3 h, saturated aqueous NH_4Cl was added and the mixture was extracted with 3 × 25 mL Et_2O. The organics were combined, washed with saturated aqueous $NaHCO_3$, water, brine, dried over $MgSO_4$, and concentrated. The crude oil was purified by flash chromatography (hexanes) to give 0.52 g (64% yield) **34** as a colorless liquid. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.68 (dd, J = 17.6, 11.0 Hz, 1H), 5.38 (t, J = 7.4 Hz, 1H), 5.21 (d, J = 17.9 Hz, 1H), 5.06 (dt, J = 11.0, 1.6 Hz, 1H), 2.11–2.19 (m, 4H), 1.34–1.57 (m, 4H), 0.91 (t, J = 7.4 Hz, 3H), 0.90 (t, J = 7.4 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 136.6, 133.2, 130.9, 113.0, 35.7, 29.6, 23.3, 22.1, 14.2, 14.0. HRMS (EI) calc. for $C_{10}H_{18}$: 138.1409, found 138.1406.

General Procedure for Cross-metathesis Reactions Using 1,2-Disubstituted 1,3-Butadienes (Table 3.2). Entry 1, 4,4,5,5-Tetramethyl-2-((1*E*,3*E*)-3-methylpenta-1,3-dienyl)-1,3,2-dioxaborolane and 4,4,5,5-tetramethyl-2-((1*E*,3*Z*)-3-methylpenta-1,3-dienyl)-1,3,2-dioxaborolane (29). To a solution of **2** (14 mg, 0.016 mmol) in CH_2Cl_2 (1 mL) was added 3-methyl-1,3-pentadiene (**28**) (27 mg, 0.32 mmol) and vinylboronate

25 (50 mg, 0.32 mmol). The solution stirred at 40 °C for 12 h, and the solvent was removed by rotary evaporation. The crude product was purified by flash chromatography (5% ethyl acetate:hexanes) to give 54 mg (80% yield, >20:1 E/Z) of the two isomers of **29**. A small amount (10%) of the cross product missing the terminal methyl group was identified by a broad singlet at 5.15 ppm in the ^{1}H NMR spectrum (terminal C=CH_2) and by HRMS (EI) (calc. for $C_{11}H_{19}BO_2$: 194.1478, found 194.1485). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.47 (d, J = 18.1 Hz, 1H, *Z*-isomer), 7.03 (d, J = 18.1 Hz, 1H, *E*-isomer), 5.76 (q, J = 6.8 Hz, 1H, *E*-isomer), 5.62 (m, 1H, *Z*-isomer), 5.55 (d, J = 18.1 Hz, 1H, *Z*-isomer), 5.42 (d, J = 18.1 Hz, 1H, *E*-isomer), 1.78 (d, J = 11.0 Hz, 3H), 1.73 (s, 3H), 1.26 (s, 12H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm) of *E*-isomer: δ 154.7, 131.9, 129.1, 83.2, 25.0, 14.5, 11.5. HRMS (EI) calc. for $C_{12}H_{21}BO_2$ (for both isomers): 208.1635, found 208.1636 and 208.1627.

Entry 2, (2*E*,4*E*)-4-methylhexa-2,4-dienyl acetate and (2*E*,4*Z*)-4-methylhexa-2,4-dienyl acetate (38). Following the general procedure for **29**, 3-methyl-1,3-pentadiene (**28**) (40 mg, 0.49 mmol), 1,4-diacetoxy-*cis*-2-butene (**6**) (167 mg, 0.97 mmol), and **2** (21 mg, 0.024 mmol) in 1.5 mL CH_2Cl_2 gave 62 mg (82% yield, >20:1 E/Z) of **38** as a colorless oil. A small amount (9%) of the cross product missing the terminal methyl group was identified by a broad singlet at 5.00 ppm in the ^{1}H NMR spectrum (terminal C=CH_2) and by HRMS (EI) (calc. for $C_8H_{12}O_2$: 140.0837, found 140.0841). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.71 (d, J = 15.5 Hz, 1H, *Z*-isomer), 6.29 (d, J = 15.7 Hz, 1H, *E*-isomer), 5.44–5.77 (m, 2H, both *E*- and *Z*-isomers), 4.64 (d, J = 7.1 Hz, 2H, *Z*-isomer), 4.59 (d, J = 7.4 Hz, 2H, *E*-isomer), 2.06 (s, 3H, *Z*-isomer), 2.05 (s, 3H, *E*-isomer), 1.81

(d, J = 15.9 Hz, 3H, both isomers), 1.72 (s, 3H, *E*-isomer), 1.70 (s, 3H, *Z*-isomer). ^{13}C NMR (75 MHz, $CDCl_3$, ppm) of *E*-isomer: δ 171.1, 139.8, 133.8, 128.8, 119.5, 65.7, 21.2, 14.1, 12.1. HRMS (EI) calc. for $C_9H_{14}O_2$ (for both isomers): 154.0994, found 154.0987 and 154.0994.

Entry 3, (3*E*,5*E*)-5-methylhepta-3,5-dien-2-one and (3*E*,5*Z*)-5-methylhepta-3,5-dien-2-one (39). Following the general procedure for **29**, 3-methyl-1,3-pentadiene (**28**) (40 mg, 0.49 mmol), methylvinylketone (**35**) (34 mg, 0.49 mmol), and **2** (21 mg, 0.024 mmol) in 1.5 mL CH_2Cl_2 gave 42 mg (70% yield, >20:1 E/Z) of **39** as a colorless oil. A small amount (7%) of the cross product missing the terminal methyl group was identified by a broad singlet at 5.40 ppm in the ^{1}H NMR spectrum (terminal C=CH_2) and by HRMS (EI) (calc. for $C_7H_{10}O$: 110.0732, found 110.0727). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.26 (d, J = 15.7 Hz, 1H, *Z*-isomer), 7.14 (d, J = 15.9 Hz, 1H, *E*-isomer), 6.15 (d, J = 15.9 Hz, 1H, *Z*-isomer), 6.05 (d, J = 15.9 Hz, 1H, *E*-isomer), 6.01 (q, J = 7.1 Hz, 1H, *E*-isomer), 5.88 (q, J = 7.1 Hz, 1H, *Z*-isomer), 2.32 (s, 3H, *Z*-isomer), 2.26 (s, 3H, *E*-isomer), 1.87–1.90 (m, 3H, *Z*-isomer), 1.83–1.87 (m, 3H, *Z*-isomer), 1.81 (d, J = 7.1 Hz, 3H, *E*-isomer), 1.76 (s, 3H, *E*-isomer). ^{13}C NMR (75 MHz, $CDCl_3$, ppm) of *E*-isomer: δ 199.2, 148.8, 137.7, 134.3, 125.1, 31.8, 27.5, 22.9. HRMS (EI) calc. for $C_8H_{12}O$ (for both isomers): 124.0888, found 124.0882 and 124.0886.

Entry 4, (5*E*,7*E*)-7-propylundeca-5,7-dienyl acetate (40). Following the general procedure for **29**, diene **34** (40 mg, 0.29 mmol), 5-hexenyl acetate (**36**) (165 mg, 1.2 mmol), and **2** (12 mg, 0.014 mmol) in 1.2 mL CH_2Cl_2 gave 56 mg (77% yield, >20:1

E/Z) of **40** as a colorless oil. The product was not separated from unreacted **36** (1.0:0.32 **40**/**36**). A small amount (12%) of the cross product missing the terminal methyl group was identified by 2 broad singlets at 5.84 and 5.88 ppm in the ^{1}H NMR spectrum (terminal C=C*H*$_2$). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.31 (d, J = 15.7 Hz, 1H), 5.64 (dt, J = 15.7, 6.9 Hz, 1H), 5.24 (t, J = 7.1 Hz, 1H), 4.06 (t, J = 6.6 Hz, 2H), 2.06–2.19 (m, 6H), 2.04 (s, 3H), 1.58–1.70 (m, 2H), 1.38–1.52 (m, 6H), 0.89 (q, J = 6.0 Hz, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 171.4, 136.1, 129.2, 128.7, 127.0, 64.6, 36.5, 33.1, 29.6, 28.3, 26.1, 23.3, 22.2, 21.2, 14.2, 14.0. HRMS (EI) calc. for $C_{16}H_{28}O_2$: 252.2089, found 252.2094.

Entry 5, (2*E*,4*E*)-4-propylocta-2,4-dienyl benzoate (41). Following the general procedure for **29**, diene **34** (40 mg, 0.29 mmol), 1,4-dibenzoyl-2-butene (**37**) (171 mg, 0.58 mmol), and **2** (12 mg, 0.014 mmol) in 1.4 mL CH_2Cl_2 gave 62 mg (79% yield, >20:1 E/Z) of **41** as a colorless oil. The product was not separated from allyl benzoate formed in the reaction (1.0:0.25 **41**/allyl benzoate). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 8.05–8.10 (m, 2H), 7.52–7.59 (m, 1H), 7.41–7.48 (m, 2H), 6.70 (dd, J = 15.8, 1.1 Hz, 1H), 5.88 (dt, J = 15.7, 6.3 Hz, 1H), 5.43 (t, J = 7.4 Hz, 1H), 4.91 (dd, J = 6.6, 1.1 Hz, 2H), 2.12–2.21 (m, 4H), 1.35–1.55 (m, 4H), 0.92 (t, J = 7.4 Hz, 3H), 0.91 (t, J = 7.4 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 166.6, 135.4, 133.1, 132.1, 131.2, 129.8, 128.8, 128.5, 122.2, 66.5, 36.2, 29.7, 23.3, 22.0, 14.2, 14.0. HRMS (EI) calc. for $C_{18}H_{24}O_2$: 272.1776, found 272.1777.

3-((Trimethylsilyl)methyl)non-1-en-3-ol (45).[14] (Trimethylsilylmethyl)magnesium chloride (1.0 M in Et_2O, 15.8 mL, 15.8 mmol) was slowly added to a solution of heptanal (**42**) (1.8 mL, 1.5 g, 13 mmol) in 14 mL of Et_2O. After 1.5 h at 40 °C, the solution was carefully quenched with saturated aqueous NH_4Cl (20 mL) and was extracted with Et_2O (3 × 25 mL). The combined organic layers were washed with 50 mL of water, 50 mL of saturated aqueous $NaHCO_3$, 50 mL of brine, were dried over $MgSO_4$, and evaporated to 2.36 g of **43** a colorless oil that was used directly in the next reaction. ^1H NMR (300 MHz, $CDCl_3$, ppm): δ 3.74–3.84 (br m, 1H), 1.20–1.46 (m, 11H), 0.83–0.90 (m, 5H), 0.04 (s, 9H). To a solution of CrO_3 (7.88 g, 78.8 mmol) in 90 mL CH_2Cl_2 was added pyridine (7.7 mL, 7.5 g, 95 mmol), and the solution bubbled and became dark orange/red. After 40 min at rt, a solution of crude **43** (2.36 g, 11. 6 mmol) in 9 mL of CH_2Cl_2 was added to the orange/red solution. The color of the reaction immediately turned brown, and after 30 seconds, the mixture was filtered through a silica gel pad. *Longer reaction times led to product decomposition.* The silica gel pad was washed with Et_2O (50 mL), and the filtrate was evaporated to a brown oil. The oil was dissolved in Et_2O (40 mL), washed with 1 M aqueous $CuSO_4$ (2 × 25 mL), dried over $MgSO_4$, and evaporated to 2.13 g of **44** as a brown oil that was used directly in the next reaction. ^1H NMR (300 MHz, $CDCl_3$, ppm): δ 2.33 (t, J = 7.1 Hz, 2H), 2.20 (s, 2H), 1.49–1.56 (m, 2H), 1.24–1.30 (br m, 6H), 0.85–0.89 (m, 3H), 0.11 (s, 9H). Vinyl magnesium bromide (1.0 M in THF, 13 mL, 13 mmol) was added slowly to a solution of crude **44** (2.13 g, 10.6 mmol) in THF (90 mL) at 0 °C. After 30 min at 0 °C, the reaction was quenched with saturated aqueous NH_4Cl (90 mL) and was extracted with Et_2O (3 × 75 mL). The combined organic layers were washed with 50 mL of water, 50 mL of saturated aqueous $NaHCO_3$, 50 mL of brine,

were dried over $MgSO_4$, and were evaporated to a yellow oil. Purification by flash chromatography (5% ethyl acetate in hexanes) afforded 1.87 g (62% over 3 steps) of **45** as a pale yellow oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 5.88 (dd, J = 17.6, 11.0 Hz, 1H), 5.17 (dd, J = 17.6, 1.6 Hz, 1H), 5.01 (dd, J = 11.0, 1.6 Hz, 1H), 1.49–1.56 (m, 2H), 1.24–1.32 (br m, 8H), 1.03 (s, 2H), 0.85–0.89 (m, 3H), 0.04 (s, 9H).

2-Hexylbuta-1,3-diene (46).[14] A suspension of **45** (1.87 g, 8.2 mmol) in 6.8 mL of acetic acid saturated with ammonium acetate was stirred at 60 °C for 20 min. The reaction mixture was poured into 100 mL of water, neutralized with saturated aqueous $NaHCO_3$, and extracted with Et_2O (3 × 50 mL). The combined organic layers were washed with 75 mL of water, 75 mL of brine, dried over $MgSO_4$, and evaporated to an oil. Purification by flash chromatography (100% hexanes) afforded 0.59 g (53% yield) of **46** as a colorless oil. Spectral data matched those reported in the literature. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.37 (dd, J = 17.6, 11.0 Hz, 1H), 5.23 (d, J = 17.6 Hz, 1H), 5.05 (d, J = 10.4 Hz, 1H), 5.00 (s, 1H), 4.98 (s, 1H), 2.20 (t, J = 7.1 Hz, 2H), 1.44–1.54 (m, 2H), 1.27–1.37 (m, 6H), 0.87–0.91 (m, 3H).

(3-Bromobut-3-enyloxy)(*tert*-butyl)dimethylsilane (48). To a solution of 3-bromo-3-buten-1-ol (**47**) (1.0 g, 6.6 mmol) in 15 mL of DMF was added imidazole (0.90 g, 13 mmol), *t*-butyldimethylsilyl chloride (1.5 g, 9.9 mmol), and dimethylaminopyridine (81 mg, 0.66 mmol). After 12 h at rt, 15 mL of water was added, and the solution was extracted with Et_2O (3 × 30 mL). The combined organic layers were washed with 45 mL of saturated aqueous $NaHCO_3$, 45 mL of brine, dried over $MgSO_4$, and concentrated.

Purification by flash chromatography (2% ethyl acetate in hexanes) afforded 1.26 g (72% yield) of **48** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 5.63 (d, J = 1.1 Hz, 1H), 5.46 (d, J = 1.6 Hz, 1H), 3.79 (t, J = 6.3 Hz, 2H), 2.62 (t, J = 6.3 Hz, 2H), 0.89 (s, 9H), 0.07 (s, 6H).

***Tert*-butyldimethyl(3-methylenepent-4-enyloxy)silane (49).** Following the same procedure as **34**, **48** (1.0 g, 3.8 mmol), vinylmagnesium bromide (1.0 M in THF, 7.5 mL, 7.5 mmol), and $Pd(PPh_3)_4$ (218 mg, 0.19 mmol) in 20 mL benzene afforded 0.61 g (76% yield) of **49** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.36 (dd, J = 17.6, 11.3 Hz, 1H), 5.24 (d, J = 17.6 Hz, 1H), 5.06 (d, J = 11.0 Hz, 1H), 5.06 (broad s, 1H), 5.03 (broad s, 1H), 3.74 (t, J = 7.1Hz, 2H), 2.46 (t, J = 7.1 Hz, 2H), 0.90 (s, 9H) 0.05 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 143.4, 139.1, 117.6, 113.5, 62.6, 35.2, 26.1, 18.6, –5.0. HRMS (EI) calc. for $C_{12}H_{24}OSi$: 212.1597, found 212.1592.

2-Iodoprop-2-en-1-ol (51).[12] Following the same procedure as **33**, propargyl alcohol (3.1 mL, 3.0 g, 54 mmol), trimethylsilyl chloride (16 mL, 14 g, 130 mmol), sodium iodide (19.3 g, 128 mmol), and water (1.2 mL, 1.2 g, 6.4 mmol) in 110 mL of acetonitrile afforded 4.67 g (46% yield) of **51** as a purple oil (15% ethyl acetate in hexanes). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.39 (q, J = 1.6 Hz, 1H), 5.85–5.87 (m, 1H), 4.17 (t, J = 1.4 Hz, 2H), 2.09 (br s, 1H).

***Tert*-butyl(2-iodoallyloxy)dimethylsilane (52).**[20] To a solution of **51** (0.52 mL, 1.0 g, 5.4 mmol) in 40 mL of CH_2Cl_2 at 0 °C was added dimethylaminopyridine (0.66 g,

5.4 mmol) and *t*-butyldimethylsilyl chloride (0.90 g, 6.0 mmol). After 12 h at rt, the reaction mixture was diluted with 40 mL of water and was extracted with 2 × 40 mL of CH_2Cl_2. The combined organic layers were washed with 40 mL of brine, dried over $MgSO_4$, and concentrated. Purification by flash chromatography afforded 1.31 g (81% yield) of **52** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.42 (q, J = 1.6 Hz, 1H), 5.81 (q, J = 1.6 Hz, 1H), 4.18 (t, J = 1.6 Hz, 2H), 0.92 (s, 9H), 0.10 (s, 6H).

***Tert*-butyldimethyl(2-methylenebut-3-enyloxy)silane (53).** Following the same procedure as **34**, **52** (1.3 g, 4.4 mmol), vinylmagnesium bromide (1M in THF, 8.7 mL, 8.7 mmol), and $Pd(PPh_3)_4$ (252 mg, 0.22 mmol) in 23 mL benzene gave 0.24 g (28% yield) of **53** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.39 (dd, J = 17.9, 11.0 Hz, 1H), 5.33 (br s, 1H), 5.17 (d, J = 18.1 Hz, 1H), 5.11 (br s, 1H), 5.04 (d, J = 11.0 Hz, 1H), 4.35 (t, J = 1.5 Hz, 2H), 0.93 (s, 9H), 0.09 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 145.1, 136.8, 114.9, 113.2, 62.6, 26.1, 18.6, –5.2. HRMS (EI) calc. for $C_{11}H_{22}OSi$: 198.1440, found 198.1449.

General Procedure for Cross-metathesis Reactions Using 2-Substituted 1,3-Butadienes (Table 3.3). Entry 1, (*E*)-4-methylenedec-2-enyl acetate (54). To a solution of **2** (12 mg, 0.014 mmol) in benzene (1.5 mL) was added 1,4-diacetoxy-*cis*-2-butene (**6**) (100 mg, 0.58 mmol) and diene **46** (40 mg, 0.29 mmol). The solution stirred at 60 °C for 12h, and the solvent was removed by rotary evaporation. The crude product was purified by flash chromatography (5% ethyl acetate:hexanes) to give 44 mg (72% yield, >20:1 E/Z) of **54** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.23 (d, J

= 16.0 Hz, 1H), 5.70 (dt, J = 15.7, 6.6 Hz, 1H), 4.96 (br s, 1H), 4.94 (br s, 1H), 4.55 (dd, J = 6.3, 1.1 Hz, 2H), 2.11 (t, J = 7.0 Hz, 2H), 2.01 (s, 3H), 1.36–1.43 (m, 2H), 1.18–1.27 (m, 6H), 0.80-0.84 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 171.0, 145.6, 136.8, 122.4, 116.7, 65.4, 32.0, 31.9, 29.4, 28.2, 22.8, 21.2, 14.3. HRMS (EI) calc. for $C_{13}H_{22}O_2$: 210.1620, found 210.1616.

Entry 2, (*E*)-4-methylenedec-2-enyl benzoate (59). Following the general procedure for **54**, diene **46** (40 mg, 0.29 mmol), 1,4-dibenzoyl-2-butene (**37**) (171 mg, 0.58 mmol), and **2** (12 mg, 0.014 mmol) in 1.4 mL benzene gave 57 mg (73% yield, >20:1 E/Z) of **59** as a colorless oil. The product was not separated from allyl benzoate formed in the reaction (1.0:0.46 **59**/allyl benzoate). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 8.05–8.09 (m, 2H), 7.53–7.60 (m, 1H), 7.44 (t, J = 7.4 Hz, 2H), 6.40 (d, J = 15.7 Hz, 1H), 5.90 (dt, J = 15.9, 6.3 Hz, 1H), 5.06 (br s, 1H), 5.03 (br s, 1H), 4.88 (dd, J = 6.3, 1.1 Hz, 2H), 2.22 (t, J = 6.9 Hz, 2H), 1.45–1.58 (m, 2H), 1.27–1.36 (m, 6H), 0.86–0.91 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 166.6, 145.6, 136.8, 133.2, 133.1, 129.8, 128.5, 122.6, 116.7, 65.8, 32.1, 31.9, 29.4, 28.2, 22.8, 14.2. HRMS (EI) calc. for $C_{18}H_{24}O_2$: 272.1776, found 272.1778.

Entry 3, (*E*)-4,4,5,5-tetramethyl-2-(3-methylenenon-1-enyl)-1,3,2-dioxaborolane (60). Following a slight modification of the general procedure for **54**, vinyl boronate **25** (89 mg, 0.58 mmol), diene **46**, (40 mg, 0.29 mmol), and **2** (25 mg, 0.029 mmol) in 1.5 mL benzene for 2 h at 60 °C (followed by the same work-up) gave 56 mg (73% yield, >20:1 E/Z) of **60** as a yellow oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.03 (d, J = 18.4

Hz, 1H), 5.59 (d, J = 18.4 Hz, 1H), 5.16 (br s, 1H), 5.13 (br s, 1H), 2.20 (t, J = 7.4 Hz, 2H), 1.41–1.48 (m, 2H), 1.20–1.34 (m, 6H), 1.27 (s, 12H), 0.85–0.89 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 152.0, 147.6, 119.3, 83.4, 31.9, 31.5, 29.5, 28.5, 25.0, 22.9, 14.3. HRMS (EI) calc. for $C_{16}H_{29}BO_2$: 264.2261, found 264.2251.

Entry 4, (*E*)-6-(*tert*-butyldimethylsilyloxy)-4-methylenehex-2-enyl benzoate (61). Following the general procedure for **54**, diene **49** (40 mg, 0.19 mmol), 1,4-dibenzoyl-2-butene (**37**) (112 mg, 0.38 mmol), and **2** (8 mg, 0.009 mmol) in 1 mL benzene gave 46 mg (70% yield, >20:1 E/Z) of **61** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 8.05–8.10 (m, 2H), 7.53–7.59 (m, 1H), 7.41–7.47 (m, 2H), 6.39 (d, J = 15.9 Hz, 1H), 5.92 (dt, J = 15.9, 6.3 Hz, 1H), 5.12 (br s, 1H), 5.07 (br s, 1H), 4.88 (d, J = 6.3 Hz, 2H), 3.75 (t, J = 7.1 Hz, 2H), 2.47 (t, J = 7.1 Hz, 2H), 0.89 (s, 9H), 0.05 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 166.5, 142.3, 136.6, 133.2, 130.4, 129.8, 128.5, 122.9, 118.6, 65.7, 62.4, 35.7, 26.1, 18.5, –5.1. HRMS (EI) calc. for $C_{20}H_{31}O_3Si$ [M+H]: 347.2043, found 347.2047.

Entry 5, (*E*)-9-(*tert*-butyldimethylsilyloxy)-7-methylenenon-5-enyl acetate (62). Following the procedure for **54**, diene **49** (40 mg, 0.19 mmol), 5-hexenyl acetate (**36**) (107 mg, 0.75 mmol), and **2** (8 mg, 0.009 mmol) in 1 mL benzene gave 46 mg (75% yield, >20:1 E/Z) of **62** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 6.05 (d, J = 15.7 Hz, 1H), 5.69 (dt, J = 15.9, 6.9 Hz, 1H), 4.94 (br s, 1H), 4.88 (br s, 1H), 4.06 (t, J = 6.6 Hz, 2H), 3.71 (t, J = 7.1 Hz, 2H), 2.43 (t, J = 6.9 Hz, 2H), 2.13 (q, J = 6.9 Hz, 2H), 2.04 (s, 3H), 1.58–1.68 (m, 2H), 1.41–1.51 (m, 2H), 0.89 (s, 9H), 0.04 (s, 6H). ^{13}C NMR

(75 MHz, $CDCl_3$, ppm): δ 171.4, 143.0, 132.7, 129.8, 115.3, 64.6, 62.8, 36.0, 32.5, 28.3, 26.2, 25.9, 21.2, 18.6, –5.1. HRMS (EI) calc. for $C_{18}H_{35}O_3Si$ [M+H]: 327.2356, found 327.2366.

Entry 6, (*E*)-*tert*-butyldimethyl(3-methylene-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pent-4-enyloxy)silane (63). Following a slight modification of the general procedure for **54**, diene **49** (40 mg, 0.19 mmol), vinyl boronate **25** (59 mg, 0.38 mmol), and **2** (16 mg, 0.019 mmol) in 1 mL benzene for 2 h at 60 °C (followed by the same work-up) gave 44 mg (69% yield, >20:1 E/Z) of **63** as a yellow oil. ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.03 (d, J = 18.4 Hz, 1H), 5.60 (d, J = 18.4 Hz, 1H), 5.23 (br s, 1H), 5.18 (br s, 1H), 3.70 (t, J = 7.1 Hz, 2H), 2.46 (dt, J = 7.1, 1.1 Hz, 2H), 1.27 (s, 12H), 0.87 (s, 9H), 0.02 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 151.8, 144.1, 121.0, 83.4, 62.4, 35.0, 26.1, 25.0, 18.5, –5.1. HRMS (EI) calc. for $C_{18}H_{35}BO_3Si$: 338.2449, found 338.2455.

Entry 7, (*E*)-*tert*-butyldimethyl(2-methylene-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-3-enyloxy)silane (64). Following a slight modification of the general procedure for **54**, diene **53** (40 mg, 0.20 mmol), vinyl boronate **25** (62 mg, 0.40 mmol), and **2** (17 mg, 0.020) in 1 mL benzene for 2 h at 60 °C (followed by the same work-up) gave 37 mg (approximately 73% pure; ~40% yield based on impurities and unreacted, inseparable boronate **25**, >20:1 E/Z) of impure **64** as a yellow oil. Peaks given in spectral data are only those corresponding to **64**. ^{1}H NMR (300 MHz, $CDCl_3$,

ppm): δ 7.06 (d, J = 18.9 Hz, 1H), 5.49 (q, J = 1.9 Hz, 1H), 5.48 (d, J = 18.7 Hz, 1H), 5.28 (br s, 1H), 4.36 (t, J = 1.6 Hz, 2H), 1.28 (s, 12H), 0.92 (s, 9H), 0.07 (s, 6H).

Entry 8, (*E*)-4-((*tert*-butyldimethylsilyloxy)methyl)penta-2,4-dienyl benzoate (65). Following the general procedure for **54**, diene **53** (40 mg, 0.20 mmol), 1,4-dibenzoyl-2-butene (**37**) (119 mg, 0.40), and **2** (9 mg, 0.01 mmol) in 1 mL benzene gave 42 mg (63% yield, >20:1 E/Z) of **65** as a pale yellow oil. Compound **65** was not separated from allyl benzoate formed in the reaction (1.0:0.55 **65**:allyl benzoate). ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 8.03–8.09 (m, 2H), 7.53–7.59 (m, 1H), 7.44 (t, J = 8.0 Hz, 2H), 6.40 (d, J = 15.9 Hz, 1H), 5.87 (dt, J = 15.9, 6.3 Hz, 1H), 5.37 (br s, 1H), 5.17 (br s, 1H), 4.86 (d, J = 6.3 Hz, 2H), 4.35 (s, 2H), 0.92 (s, 9H), 0.09 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm): δ 166.5, 144.0, 134.0, 133.2, 129.8, 128.5, 122.7, 118.4, 116.1, 65.8, 62.9, 26.1, 18.5, –5.2. HRMS (EI) calc. for $C_{19}H_{29}O_3Si$ [M+H]: 333.1886, found 333.1888.

(*E*)-1-(3-methylpenta-1,3-dienyl)benzene (71). To a solution of **2** (14 mg, 0.016 mmol) in benzene (1.5 mL) was added vinylboronate **25** (50 mg, 0.32 mmol) and diene **28** (26 mg, 0.32 mmol), and the solution stirred at 40 °C for 2.5 h. The reaction solution was cooled to rt, and $Pd(PPh_3)_4$ (11 mg, 0.0097 mmol), bromobenzene (50 mg, 0.32 mmol), and NaOEt (2M in EtOH, 0.46 mL, 0.91 mmol) were added. The solution stirred at 80 °C for 5 h. The reaction mixture was purified by flash chromatography (100% hexanes) to give 23 mg (45% yield) of **71** as a colorless oil. A small amount (13%) of the cross product missing the terminal methyl group was identified by two broad singlets at 5.09 ppm and 5.14 ppm in the ^{1}H NMR spectrum (terminal C=CH_2). Characterization

data matched those in the literature.[21] ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 7.41–7.48 (m, 2H, both *E*- and *Z*-isomers), 7.28–7.36 (m, 2H, both *E*- and *Z*-isomers), 7.18–7.26 (m, 1H, both *E*- and *Z*-isomers), 6.90 (d, J = 16.2 Hz, 1H, *Z*-isomer), 6.83 (d, J = 16.2 Hz, 1H, *E*-isomer), 6.57 (d, J = 15.9 Hz, 1H, *Z*-isomer), 6.46 (d, J = 15.9 Hz, 1H, *E*-isomer), 5.73 (q, J = 7.1 Hz, 1H, *E*-isomer), 5.56 (q, J = 7.1 Hz, 1H, *Z*-isomer), 1.95 (m, 3H, *Z*-isomer), 1.88 (t, J = 1.1 Hz, 3H, *E*-isomer), 1.82 (d, J = 7.1 Hz, 3H, *E*-isomer); terminal methyl resonance of *Z*-isomer overlaps with those of the major isomer.

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